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Redundancy Concepts to Increase Transmission Reliability in Wireless Industrial LANs (Extended Version)

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Berlin, April 2005

TKN Technical Report TKN-05-002

TKN Technical Reports Series

Editor: Prof. Dr.-Ing. Adam Wolisz

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Abstract

Wireless LAN are potentially an attractive networking technology for industrial applications. A major obstacle towards the fulfillment of hard real-time requirements is the error-prone behavior of wireless channels. A common approach to combat channel errors and to increase the probability of a message being transmitted successfully before a prescribed deadline is to employ redundancy and diversity techniques. In this paper we introduce a specific transmit diversity scheme, called antenna redundancy, and integrate this with two other redundancy / diversity schemes, namely error-correcting codes and multicopy-ARQ, into a common framework allowing to investigate the tradeoffs between these methods. In antenna redundancy the wireless stations are equipped with a single antenna, but the base station / access point has several of them. For each trial to transmit a packet from the base station to the wireless station another antenna is used. The relative benefits of using FEC versus adding antennas are investigated. One important result obtained analytically and by simulation is that for independent Gilbert-Elliot channels between the base station antennas and the wireless station the antenna redundancy scheme decreases the probability of missing a deadline by approximately an order of magnitude per additional antenna. As a second benefit, antenna redundancy decreases the number of transmission trials needed to transmit a message successfully, thus saving bandwidth.

Index Terms

wireless industrial LANs, redundancy, FEC, multicopy-ARQ, antenna redundancy, antenna reuse strategy

I. Introduction

THE idea to use wireless technology on the factory floor is appealing, and some work has been done to investigate its feasibility and to find sound technical approaches [1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. All approaches are faced to, and some of them seriously consider the problem of supporting hard real-time guarantees despite the "unfriendliness" of wireless links, which show high error rates and time-varying error behavior. It is argued in in [3] that deterministic guarantees to keep deadlines are not appropriate for wireless links and therefore *stochastic guarantees* become important. Clearly, the goal is to increase the probability of successful and deadline-preserving delivery of safety-critical or periodic messages. Some strategies to achieve this are: a) improving the physical layer (e.g. find better modulation schemes, better receivers, increase transmit power, directional antennas, antenna diversity); b) proper frequency and interference planning; c) finding good locations for the wireless stations and access points [11]; and d) improve the lower layer protocols, namely the medium access control (MAC) and link-layer protocols. In this paper we focus on the last approach and look into the abilities of three selected redundancy / diversity schemes to preserve deadlines.

Forward error correction (FEC) schemes add overhead bits to user data in order to correct a number of bit errors [12], [13]. In *automatic-repeat-request (ARQ)* protocols a checksum is appended to each packet. This checksum allows the receiver to detect almost all errors, but not to correct them. If the receiver detects an erroneous packet, it requests a retransmission [14]. In *hybrid schemes* ARQ and FEC are combined. One simple example of a hybrid scheme is to apply a light FEC code to each packet and to let the ARQ protocol handle the uncorrectable errors. Another example are multicopy-ARQ protocols [15]. In multicopy-ARQ multiple copies of the same packet are transmitted as a *batch*. The packet batch is retransmitted only when the receiver fails to receive any of these copies. Multicopy-ARQ can also be viewed as a *time-diversity* scheme.

Other diversity schemes take advantage of the *spatial diversity* of wireless links: if a station A transmits a packet to the distant stations B and C, then it might well happen that B receives the packet correctly, while C experiences an error. Conversely, if two distant stations A and B transmit a packet to C, C might fail to receive A's packet but B's packet is received correctly. In [3] spatial diversity and retransmissions of the ARQ protocol are considered *jointly*: if station A's packet to station C fails but station B has "incidentally" picked up the packet, B could try its luck by sending it to C using the (different) spatial channel between B and C. This kind of "channel hopping" for retransmissions is especially fruitful if the channels are independent and exhibit *bursty errors*: if a packet transmitted at time t_0 over channel c_1 is received erroneously and the channel is bursty, then the probability that a retransmission at time $t_0 + \tau$ over c_1 also erroneous, can reach high values for small to moderate values of τ. Error bursts on wireless channels often last some tens of milliseconds, which covers multiple packets and renders immediate retransmissions nearly useless. If another channel is used for the retransmission the chances to deliver the packet successfully and to preserve given deadlines can be higher.

The first contribution of this paper is an extension and generalization of the approach to use different spatial channels for retransmissions [3]. This approach provides a kind of transmit diversity, however, for brevity it is henceforth referred to as *antenna redundancy*. The idea is to equip a central station (base station, access point) with a number K of spatially separated antennas whereas for a wireless station a single antenna suffices. For downlink packets the central station switches the antennas in a round-robin manner upon retransmissions. As an example, the first packet is transmitted on antenna 1, the first retransmission on antenna 2, the second retransmission on antenna 3 and so forth. If the antennas are placed appropriately, a wireless station separated by an obstacle from some antennas might still be in reach of other antennas.[1] As compared to other transmit diversity schemes this approach places does not require complex signal processing at the receiver.

As a second contribution, we define a downlink transmission scheme combining antenna redundancy, multicopy-ARQ and the use of (light) FEC for every packet. We look onto this scheme from a specific perspective: one of the most important requirements in industrial communications is to transmit time-critical packets before their deadline, and consequently we investigate an important stochastic measure for this, the *failure probability*. The latter is defined here as the probability for an important downlink packet to miss a prespecified deadline. Such important downlink packets can be for example actuator commands.

The third contribution of this paper is an analytical and simulation-based evaluation of the integrated schemes failure probability for different combinations of the number of antennas, FEC strength and batch sizes. A key parameter for the performance analysis is the channel error model. To facilitate analysis, we focus to the case of independent channels between the antennas and the wireless station. For any single of these channels we use two different stochastic models: the Gilbert-Elliot model [16], [17] and a Semi-Markov model. The Gilbert-Elliot model is quite popular in performance evaluation of wireless protocols because of the following reasons: it is sufficiently complex to express bursty error behavior (as it is typical for wireless channels), it is sufficiently simple to be analytically tractable and it has been shown both analytically and experimentally that it reasonably approximates the error statistics of certain types of wireless fading channels. The Semi-Markov model is a modification of the Gilbert-Elliot model, giving greater flexibility in modeling the duration of channel fades. The analytical method outlined in this paper is constrained to the case of Gilbert-Elliot channels, the Semi-Markov model is investigated by simulation. The fact that the analytical model and the simulation model give the same results for the Gilbert-Elliot channel validates the simulation model and makes the results for other channel types credible.

Our results show that under these assumptions antenna redundancy alone can significantly decrease the failure probability, in our example the reduction is almost an order of magnitude per additional

[1] Alternatively, a number K of tightly synchronized and coupled base stations can be used to achieve the same effect. However, this is not explored further in this paper.

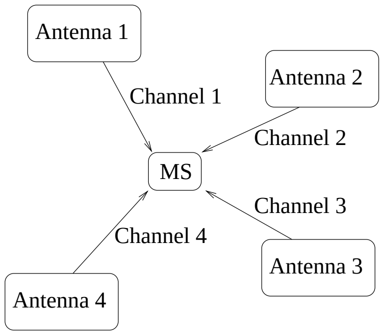

Fig. 1. Example Scenario with four Antennas and a single Mobile Station (MS)

antenna. Furthermore, antenna redundancy can decrease the necessary number of trials to transmit a packet successfully, thus saving bandwidth. Further bandwidth can be saved by using an additional optimization, the *antenna reuse policy*: the first trial of a new packet uses the antenna over which the last successful packet was transmitted, instead of always starting at antenna one. We show that additional reductions in bandwidth expenditure can be made when the interarrival time of new packets is on the same order or smaller than the average duration of a good channel period. This result is applicable to industrial communication systems, as periodic data streams often have periods in the range of (tens of) milliseconds, and on the other hand practical fading channels have an average good channel state durations in the order of tens of milliseconds. We also shed some light of the relative benefits when combining antenna redundancy, multicopy-ARQ and the light FEC / ARQ scheme. The effectiveness of multicopy-ARQ depends on the actual error burst lengths. Clearly, in the presence of bit errors FEC also reduces the probability of a deadline miss, however, at the cost of increased overhead. If the error rates during bad channel periods are too high, FEC is often useless whereas antenna redundancy gives gains. On the other hand, for low error rates FEC is more effective in decreasing the failure probability than antenna redundancy. The developed models allow to explore the different tradeoffs and to find good solutions for known channel conditions.

This paper is structured as follows: in the next Section II we explain in greater detail the system model and our approaches for antenna redundancy, multicopy-ARQ and FEC. Following this, in Section III we discuss the most important general characteristics of the error behavior of wireless channels and introduce the Gilbert-Elliot model. In Section IV we present the analytical model for the probability of a combination of antenna redundancy, multicopy-ARQ and FEC when operated over a Gilbert-Elliot channel to miss a prespecified deadline. After this we discuss in Section V the simulation setup and the set of fixed parameters used throughout the simulations and analytical evaluations presented in Section VI. Finally, in Section VII we give our conclusions and discuss future research directions.

Some of this papers results were already presented in [18].

II. Approach and system model

We consider a system consisting of one central station having K spatially distributed antennas, numbered from 1 to K. The mutual distance between the antennas is assumed to be much larger than the wavelength used by the wireless transmission system (see below). There is a single mobile station (MS), and a separate wireless channel between the MS and each antenna (see Figure 1); the channel between antenna i and the MS is denoted as C_i. The notion of a wireless channel used here includes the wireless transceivers of central station and wireless station as well as the "air" between the antennas. Hence, in this paper we regard a wireless channel primarily as an entity generating bit errors during data transmission.

We assume that the channels $C_1, \ldots, C_K$ are stochastically independent. This assumption is reasonable if the wireless channel errors can be attributed to multipath fading: for this case it is well-known that beyond a geographical distance of half a wavelength between the antennas the spatial channels are often found to be uncorrelated [19, Chap.7]. We make the stronger assumption of independence because of its theoretical utility. If the error behavior would be dominated by interference (e.g. the MS is located close to a microwave oven), then different channels would probably show strongly correlated error behavior.

First we present the combined transmission scheme integrating antenna redundancy, multicopy-ARQ and the light FEC/ARQ protocol, before explaining the components. We denote as a *request* a piece of data which has to be transmitted within a prescribed deadline from the central station to wireless / mobile station (MS). This piece of data is encapsulated into a *packet*. The following procedure is used to handle a request: the central station transmits a batch of $R \geq 1$ identical copies of the packet over antenna 1. Each packet is equipped with an error-correcting code capable of correcting up to $t \geq 0$ errors in $l > t$ bits. When the MS receives any of the R packets correctly, it sends an acknowledgement (ack) frame. We assume the ack to be transmitted in zero time and error-free. Otherwise the central station retransmits the R packets immediately over antenna 2. If there is again no ack, the central station retransmits the R packets immediately over antenna 3, and so forth. After the deadline has passed without getting an ack, the central station discards the request and marks it as *failure*. In the other case the request (one of its packets) was successfully received by the MS and we have a *success*. The *deadline* d is defined as follows:

$$d = \frac{D \cdot l}{b} \text{ seconds}$$

where b is the raw data rate of the channel in bits/s, l is the packet length in bits, and $D \in \mathbb{N}$ with $D > 1$ is the admissible number of trials. The main *performance measure* used in this paper is the *failure probability* $p_F(D)$ for an important downlink request to miss its deadline. Important downlink requests can for example be actuator commands.

Next we discuss the "ingredients" of the combined scheme. In *multicopy-ARQ* the transmitter transmits a batch of $R \in \mathbb{N}$ back-to-back copies of the same packet instead of only a single one. The MS sends an acknowledgement when it manages to receive at least one of those copies. The receiving MS can filter out further copies of the same packet by means of sequence numbers provided by the ARQ protocol.

The second scheme is the combination of FEC and ARQ. As for the ARQ protocol, we assume the alternating-bit protocol, which is simple to implement and provides sequence numbers. The general idea of FEC is to add a number of redundancy bits to the data bits to be able to correct a few bit errors. Todays most often used FEC schemes can be broadly divided into block codes, convolutional codes and turbo codes [12], [13], [20]. FEC has some disadvantages: its overhead reduces the user bandwidth and is expended even during good channel periods, in case of very high bit error rates an enormous overhead would be needed, and furthermore FEC can only combat bit errors but no packet losses.[2] Here we make the simplistic assumption that we can correct a number t of bit errors in a packet of l bits length, no matter where exactly the bit errors are located in the packet. The case of $t = 0$ corresponds to no error correction capability. We assume that uncorrectable bit error patterns are detected reliably, for example by means of additional checksums.

In the antenna redundancy approach with K antennas a packet / batch directed from the central station to the MS is first transmitted over antenna 1. If there is need for a retransmission, then antenna 2 is used. If another retransmission is needed, antenna 3 is used and so forth, until the packet is successfully received or a prescribed deadline for transmitting the request expires. The antennas are used in round-robin fashion. If all channels are independent, the transmissions can be regarded as a series of independent Bernoulli trials as long as no antenna is re-used. It is important to note that the receiving MS needs only a single antenna and can be kept simple. In the uplink direction the K antennas provide *receiver diversity* [21]. If the K antennas are equipped with full transceivers each delivering a stream of bits, the central station might try to figure out the correct packet by performing a bit-by-bit majority voting procedure [22, Chapter 4]. However, we do not consider this any more in this paper.

[2] *Packet losses* occur due to the inability of the receiver to acquire bit synchronization, whereas bit errors can occur only if the receiver is already synchronized.

In the downlink direction antenna redundancy belongs to the class of transmit diversity schemes [19, Chapter 7]. Its most important property is that the receiver requires only a single antenna and can be kept simple as compared to other transmit diversity schemes, most notably MIMO (multiple input, multiple output) systems. The latter employ multiple transmit and multiple receive antennas and achieve an increase in channel capacity at the cost of significant computational complexity [23], [24], which translates directly into increased system costs. The antenna redundancy scheme is closest in spirit to [25] (which transmits on two antennas simultaneously) or to the CDMA-based soft handover technique employed in UMTS [26].

III. Error behavior of wireless channels

It is widely accepted that transmission over wireless channels is much more error-prone than over cable-based media. The error patterns that lower layer protocols (MAC, link layer protocols) are exposed to, are influenced by multiple factors, some of them are: frequency, modulation scheme, interference, propagation environment, mobility and the imperfections of transmitter and receiver circuitry. With respect to creating a wireless industrial LAN the nowadays popular, mature, standardized and constantly evolving IEEE 802.11 wireless LAN technology [27], [28], [29] is an attractive choice. Several measurement studies investigate the error behavior of IEEE 802.11-compliant radio modems in different environments (e.g. [4], [30], [31], [32], [33], [34]), some of them in industrial environments ([4], [30]). These measurements showed some characteristics which we take as basis and motivation for this work:

- Time-varying behavior.
- Large variability in the distributions of the lengths of error bursts and error-free periods (called *runs*). Some measurements even revealed heavy-tailed burst and run length distributions [35].
- Bursty errors / long-lasting correlation.
- Sometimes high bit error rates up to $10^{-3} \ldots 10^{-2}$.

A. Stochastic models for generating bit errors

For simulation-based and analytical performance evaluation of communication protocols one often uses stochastic channel error models. For packet- and bit-level error models often simple stochastic processes like for example Markov chains are used, which in turn rely on a set of parameters. Roughly speaking, there is a tradeoff between the model complexity (measured by number of parameters) and the models accuracy in matching certain error statistics, as they are desired by the models user or found in error traces.

A wide range of digital error models is discussed in [36], and specific model classes describing the measurement data of [30] are discussed in [35]. In this paper we focus on two different models: the popular *Gilbert-Elliot model* and a *Semi-Markov model*, which in fact is a variation of the Gilbert-Elliot model. The Gilbert-Elliot model is of utmost importance for this paper, since it is complex enough to capture burstiness, simple enough to be treated analytically and it has been shown experimentally and analytically that it provides a reasonable approximation to the channel error characteristics of certain types of wireless fading channels [37]. Furthermore, it is used in numerous performance evaluation studies investigating lower layer protocols over wireless channels and thus makes results better comparable.

B. The time-homogeneous discrete-time Gilbert-Elliot channel model

Let us assume two stations A and B connected through a wireless channel. Station A wants to transmit a packet of length l bits to station B. The channel error behavior is governed by a discrete-time Gilbert-Elliot model [16], [17], which produces either correct bits or erroneous bits.[3] The Gilbert-Elliot model is a two-state time-homogeneous discrete time Markov chain (TH-DTMC). The model works with slotted

[3]For simplicity we do not distinguish between bit errors and packet losses [30]. The latter can be approximated by chosing high error rates during the bad state.

time, the state transitions happen at times $(X_n)_{n\in\mathbb{N}_0}$. The time between X_n and X_{n+1} corresponds to one bit duration. The state space of the TH-DTMC contains only the two states 0 (=*good*) and 1 (=*bad*). The initial state X_0 is selected randomly.

The state of slot X_{n+1} is determined at its beginning by executing a Bernoulli experiment, whichs parameter depends on the previous state X_n: if $X_n = 0$ then $X_{n+1} = 0$ with probability $p_{g,g}$ and $X_{n+1} = 1$ with probability $1 - p_{g,g}$. Accordingly, if $X_n = 1$ then $X_{n+1} = 1$ with probability $p_{b,b}$ and $X_{n+1} = 0$ with probability $1 - p_{b,b}$. The state transition matrix of the TH-DTMC is thus given by:

$$\mathbf{P} = \begin{pmatrix} p_{g,g} & 1 - p_{g,g} \\ 1 - p_{b,b} & p_{b,b} \end{pmatrix}$$

The steady-state vector $\pi = (\pi_0, \pi_1)$ of $\mathbf{P}$ is given by:

$$\begin{aligned} \pi_0 &= \frac{1 - p_{b,b}}{2 - (p_{g,g} + p_{b,b})} \\ \pi_1 &= \frac{1 - p_{g,g}}{2 - (p_{g,g} + p_{b,b})} \end{aligned}$$

The matrix $\mathbf{P}$ has the eigenvalues $\lambda_1 = 1$ and $\lambda_2 = p_{g,g} + p_{b,b} - 1$. Using diagonalization and some algebra one can show that with $z(k) := (p_{g,g} + p_{b,b} - 1)^k$ for some integer k, we can compute the matrix power $\mathbf{P}^k$ as follows:

$$\mathbf{P}^k = \frac{1}{p_{g,g} + p_{b,b} - 2} \cdot \left[z(k) \begin{pmatrix} p_{g,g} - 1 & 1 - p_{g,g} \\ 1 - p_{b,b} & p_{b,b} - 1 \end{pmatrix} + \begin{pmatrix} p_{b,b} - 1 & p_{g,g} - 1 \\ p_{b,b} - 1 & p_{g,g} - 1 \end{pmatrix} \right]$$

It is not hard to see that for $p_{g,g} + p_{b,b} \in (1,2)$ the matrix entries $[[\mathbf{P}^k]]_{1,1}$ and $[[\mathbf{P}^k]]_{2,2}$ are monotonically decreasing for increasing k, while $[[\mathbf{P}^k]]_{1,2}$ and $[[\mathbf{P}^k]]_{2,1}$ are monotonically increasing for increasing k. Thus, for the autocorrelation function $R(t)$ we have:

$$\begin{aligned} R(k) &= E[X_0 X_k] = \Pr[X_0 = 1, X_k = 1] \\ &= \Pr[X_k = 1 \,|X_0 = 1] \cdot \Pr[X_0 = 1] \\ &= [[\mathbf{P}^k]]_{2,2} \cdot \Pr[X_0 = 1] \end{aligned}$$

which translates into an exponentially decreasing autocorrelation (short term dependence) / vanishing channel memory.

The state holding times are geometrically distributed and hence are *memoryless*.[4] The mean state holding times for the good state $E[H_0]$ and the mean state holding time for the bad state $E[H_1]$ are given by:

$$E[H_0] = \frac{1}{1 - p_{g,g}} \qquad E[H_1] = \frac{1}{1 - p_{b,b}}$$

During the bad channel states each transmitted bit is subjected to an independent Bernoulli experiment to determine whether it is transmitted erroneously or correct. Let p be the bit error probability. In the good state no bit errors occur.

[4]Be X a real-valued nonnegative random variable. X is called memoryless, if for all $s, t \in \mathbb{R}_0^+$ ($\mathbb{N}_0$for discrete random variables) the following holds:

$$\Pr[X > s + t \,|X > s] = \Pr[X > t]$$

The geometric distribution is the only discrete memoryless distribution, while the exponential distribution is the only continuous one.

C. The semi-Markov model

In this paper we use a specific Semi-Markov model as a second model. The model is in fact a variation of the Gilbert-Elliot model: it has the same two states *good* and *bad*, but the state holding times have a (quantized) lognormal distribution instead of a geometric distribution. The lognormal distribution generates positive real numbers with arbitrary mean and variance (equivalently: coefficient of variation). These can be chosen freely and are used to investigate the influence of highly variable state holding times.

IV. ANALYTICAL MODELING

In this section we derive an analytical model for the failure probability $p_F(D)$, that a request transmitted from the central station with K antennas to the MS could not be delivered successfully (i.e. acknowledged) within the deadline of D packets over K independent Gilbert-Elliot channels. This is a key performance measure for industrial networks. Developing such an analytic model is not only interesting in itself, but is also a valuable tool for verifying a simulation model of the same system. A working and valid simulation model is inevitably needed when more complex channel types are to be investigated for which no analytical solution exists.

The derivation proceeds in two steps:

- First we focus on transmission of a single packet over a single channel following the Gilbert-Elliot model, which was chosen due to its analytic tractability and its ability to express bursty channel behavior. Two different cases are investigated: a) packet transmission when the channel is in the steady-state (Section IV-A) , and b) packet transmission some short time after a previous packet has experienced errors on the same channel and the channel might thus still be in the bad state (Section IV-B). The former case corresponds to the first trial to transmit a packet, the latter case to the first retransmission, and by the time-homogeneity and memoryless property of the Gilbert-Elliot channel, to any subsequent retransmission on the same channel.
- These building blocks are used to calculate the overall probability that a request could not be transmitted within a prescribed deadline (Section IV-C).

In Section IV-D some first consequences are derived from the developed analytical model.

A. Steady-state packet error probability over a Gilbert-Elliot channel

Let us assume that the TH-DTMC has reached its steady state, however, for notational convenience we assume that we start at time X_0, where a request arrives at the central station. We introduce the random variable $T_i(l)$ denoting the number of bit errors which occur in a packet of length l bits when starting transmission at time X_i. Be $p_S(l)$ the probability that a packet of length l bits being transmitted over a steady-state Gilbert-Elliot channel at time X_0 is received erroneously (i.e. has more than t bit errors). This probability is then given by:

$$\begin{aligned} p_S(l) &= \sum_{n=t+1}^{l} \Pr\left[T_0(l) = n\right] \\ &= \sum_{n=t+1}^{l} \{\Pr\left[T_0(l) = n \,|X_0 = 0\right] \cdot \Pr\left[X_0 = 0\right] \\ &\qquad + \Pr\left[T_0(l) = n \,|X_0 = 1\right] \cdot \Pr\left[X_0 = 1\right]\} \end{aligned}$$

Clearly, since we assume the TH-DTMC $\mathbf{P}$ to be in steady state, we have that:

$$\Pr\left[X_0 = 0\right] = \pi_0 = \frac{1-p_{b,b}}{2-(p_{g,g}+p_{b,b})}$$
$$\Pr\left[X_0 = 1\right] = \pi_1 = \frac{1-p_{g,g}}{2-(p_{g,g}+p_{b,b})}$$

We are now faced to the calculation of $\Pr[T_0(l) = n \,|X_0 = 0]$ and $\Pr[T_0(l) = n \,|X_0 = 1]$. We have developed an analytical model for the general case (see appendix), allowing an arbitrary number of state changes during the packets transmission time, as well as arbitrary ways to distribute the n bit errors over the bad periods during the packet. However, even with explicit formulae the model consumed significant computation time. To resolve this, we introduce the restriction that at most one state change happens during a packet. For industrial applications this seems to be a reasonable approximation, since the important packets (alarms, cyclic data packets) tend to be short compared to the timescales of changes in wireless channels [38]. For example, for a bit rate b of 1 Mbit/s safety-critical packets will likely be no longer than 500 μs, while channel fluctuations occur on timescales of tens of milliseconds. Indeed, a comparison between the exact model and the approximate model revealed virtually no loss in precision.

We can express $\Pr[T_0(l) = n \,|X_0 = 0]$ as follows:

$$\Pr[T_0(l) = n \,|X_0 = 0] = \sum_{k=1}^{l-n} b(n; l-k, p)(1 - p_{g,g})p_{g,g}^k$$

where $b(k; n, p) = \binom{n}{k} p^k (1-p)^{n-k}$ is the binomial distribution. Each term $b(n; l-k, p)(1 - p_{g,g})p_{g,g}^k$ corresponds to the probability that a good burst starting at X_0 lasts until X_k and that there are n bit errors in the remaining $l - k$ bits. This representation is valid since the bit errors during the bad state are assumed independent, and the state holding time of the good state is geometrically distributed. Furthermore, there have to be at least n bits in the bad state at the end of the packet.

For the computation of $\Pr[T_0(l) = n \,|X_0 = 1]$ we have to take into account that the first bit of the packet is definitely transmitted during a bad channel state / error burst. Using this and the law of total probability, we have:

$$\begin{aligned}
&\Pr[T_0(l) = n \,|X_0 = 1] = \\
&\quad \Pr[\text{burst lasts for } n \text{ bits, } n \text{ errors in } n \text{ bits}] \\
&\quad + \Pr[\text{burst lasts for } n+1 \text{ bits, } n \text{ errors in } n+1 \text{ bits}] \\
&\quad + \ldots \\
&\quad + \Pr[\text{burst lasts for } l-1 \text{ bits, } n \text{ errors in } l-1 \text{ bits}] \\
&\quad + \Pr[\text{burst lasts for } k \geq l \text{ bits, } n \text{ errors in } l \text{ bits}] \\
&= \sum_{k=n}^{l-1} b(n; k, p)(1 - p_{b,b})p_{b,b}^{k-1} \\
&\quad + b(n; l, p) \sum_{k=l}^{\infty} (1 - p_{b,b})p_{b,b}^k \\
&= \sum_{k=n}^{l-1} b(n; k, p)(1 - p_{b,b})p_{b,b}^{k-1} + b(n; l, p)p_{b,b}^l
\end{aligned}$$

The lowered exponent $k - 1$ in the first sum accounts for the fact that the first bit is transmitted in bad state anyway.

Putting everything together, we have:

$$\begin{aligned}
&\Pr[T_0(l) = n] = \\
&\quad \frac{1 - p_{b,b}}{2 - (p_{g,g} + p_{b,b})} \cdot \left(\sum_{k=1}^{l-n} b(n; l-k, p)(1 - p_{g,g})p_{g,g}^k \right) \\
&+ \quad \frac{1 - p_{g,g}}{2 - (p_{g,g} + p_{b,b})}
\end{aligned}$$

$$\cdot \left(\sum_{k=n}^{l-1} b(n;k,p)(1-p_{b,b})p_{b,b}^{k-1} + b(n;l,p)p_{b,b}^{l} \right)$$

B. Conditional packet error probability

The next building block considers retransmissions over a channel which already showed errors. Let us assume that a station transmits a packet at time X_0, and the packet experiences more than t bit errors. If the station starts a retransmission at some later time X_m ($m \geq l$), then we are interested in the probability that this retransmission fails, too. Intuitively, for the Gilbert-Elliot channel one might expect that this probability is larger than the steady-state probability $p_S(l)$, since the channel has some memory and is known to have been in the bad state during X_0 until X_l. Hence, if the retransmission is scheduled too early, the packet error probability is increased.

More precisely, we are interested in calculating the probability

$$p_C(l,m) = \Pr\left[T_m(l) > t\right] = \sum_{n=t+1}^{l} \Pr\left[T_m(l) = n\right]$$

for some starting time $m \geq l$. To compute the probability $\Pr\left[T_m(l) = n\right]$, we start as follows:

$$\begin{aligned} &\Pr\left[T_m(l) = n\right] = \\ &\qquad \Pr\left[T_m(l) = n \,|X_m = 0\right] \cdot \Pr\left[X_m = 0\right] \\ &\quad + \quad \Pr\left[T_m(l) = n \,|X_m = 1\right] \cdot \Pr\left[X_m = 1\right] \end{aligned}$$

Since the TH-DTMC is time-homogeneous, we can write:

$$\Pr\left[T_m(l) = n \,|X_m = x\right] \quad = \quad \Pr\left[T_0(l) = n \,|X_0 = x\right]$$

for $x \in \{0,1\}$ and we can use the above expressions.

For computation of $\Pr\left[X_m = 0\right]$ and $\Pr\left[X_m = 1\right]$ we condition on the channel state at the time where the original packet ends, X_l, as follows:

$$\begin{aligned} &\Pr\left[X_m = x\right] = \\ &\qquad \Pr\left[X_m = x \,|X_l = 0\right] \Pr\left[X_l = 0\right] \\ &\quad + \quad \Pr\left[X_m = x \,|X_l = 1\right] \Pr\left[X_l = 1\right] \end{aligned}$$

We can again take advantage of the time-homogeneity and write:

$$\begin{aligned} \Pr\left[X_m = j \,|X_l = i\right] &= \Pr\left[X_{m-l} = j \,|X_0 = i\right] \\ &= [[\mathbf{P}^{m-l}]]_{i+1,j+1} \end{aligned}$$

To compute $\Pr\left[X_l = 0\right]$ we condition on X_{l-1} which is the channel state during the last transmitted bit of the first (and erroneous) packet. We can write:

$$\begin{aligned} &\Pr\left[X_l = 0\right] = \\ &\qquad p_{g,g} \cdot \Pr\left[X_{l-1} = 0\right] + (1-p_{b,b}) \cdot (1 - \Pr\left[X_{l-1} = 0\right]) \end{aligned}$$

The event $X_{l-1} = 0$, by the assumption of having at most one state change, requires that $X_0 = \ldots = X_t = 1$ (i.e. the packet has to start during a bad burst and this must span at least $t+1$ bits) and that the state change happens at one of the time instants $X_{t+1}, \ldots X_{l-1}$. Hence,

$$\Pr\left[X_{l-1} = 0\right] = \sum_{k=t+1}^{l-1} (1-p_{b,b})p_{b,b}^{k}$$

This gives us:

$$
\begin{aligned}
&\Pr\left[X_l = 0\right] = \\
&\quad p_{g,g} \cdot \sum_{k=t+1}^{l-1} (1 - p_{b,b}) p_{b,b}^k \\
&+ \quad (1 - p_{b,b}) \cdot \left(1 - \sum_{k=t+1}^{l-1} (1 - p_{b,b}) p_{b,b}^k \right)
\end{aligned}
$$

and clearly $\Pr\left[X_l = 1\right]$ is given by:

$$\Pr\left[X_l = 1\right] = 1 - \Pr\left[X_l = 0\right]$$

Putting everything together and using the shorthand $p_{l,0} = \Pr\left[X_l = 0\right]$ we have:

$$
\begin{aligned}
&\Pr\left[T_m(l) = n\right] = \\
&\quad \Pr\left[T_0(l) = n \,|\, X_0 = 0\right] \\
&\quad \cdot \left(p_{l,0} \cdot [[\mathbf{P}^{m-l}]]_{1,1} + (1 - p_{l,0}) \cdot [[\mathbf{P}^{m-l}]]_{2,1}\right) \\
&+ \quad \Pr\left[T_0(l) = n \,|\, X_0 = 1\right] \\
&\quad \cdot \left(p_{l,0} \cdot [[\mathbf{P}^{m-l}]]_{1,2} + (1 - p_{l,0}) \cdot [[\mathbf{P}^{m-l}]]_{2,2}\right)
\end{aligned}
$$

and finally, the overall probability $p_C(l, m)$ that a packet of length l transmitted at some time $m \geq t$ is received erroneously, given that the same packet transmitted at time 0 is received erroneously, is given by:

$$p_C(l, m) = \sum_{n=t+1}^{l} \Pr\left[T_m(l) = n\right]$$

For fixed $n > 0$ the probability $\Pr\left[T_m(l) = n\right]$ decreases with increasing m, at least under the following conditions:

- $p_{g,g} + p_{b,b} \in (1, 2)$
- $\Pr\left[X_l = 0\right]$ is small and can be neglected
- $\Pr\left[T_0(l) = n \,|\, X_0 = 0\right] \leq \Pr\left[T_0(l) = n \,|\, X_0 = 1\right]$

(to see this, it suffices to apply some algebra to $\Pr\left[T_m(l) = n\right] - \Pr\left[T_{m+1}(l) = n\right]$, and to drop the terms containing $\Pr\left[X_l = 0\right]$). For $p_{g,g}$ and $p_{b,b}$ close to 1 these conditions can be fulfilled.

A numerical example is shown in Figure 2 with $l = 416$ bits, $t = 0$, and $p = 1$, the same values as used in Section V. Furthermore, we have set the mean state holding time of the good channel state $E\left[H_0\right]$ to 65.000 bits ($\implies p_{g,g} \approx 0.9999846153846$), while the mean bad state holding time is 10.000 bits ($\implies p_{b,b} = 0.9999$).

C. *Failure probability for K antennas with round-robin scheme*

1) Case 1: $K \cdot R \geq D$: In this simple case each antenna gets at most one chance to transmit its R copies to the MS. There are $K_1 := \lfloor \frac{D}{R} \rfloor$ antennas which can transmit full batches of R packets. All their channels $C_1, \ldots C_{K_1}$ are independent. The last antenna, called *slack antenna* gets the chance to transmit $R_S := D \mod R$ packets of its batch.

If a single of the K_1 antennas fails with probability $p(R)$ to successfully transmit one of its R packets, and the slack antenna fails with probability $p'(R)$, then the overall failure probability is given by:

$$p_F(D) = (p(R))^{K_1} \cdot p'(R)$$

since the trials can be seen as a sequence of independent Bernoulli experiments.

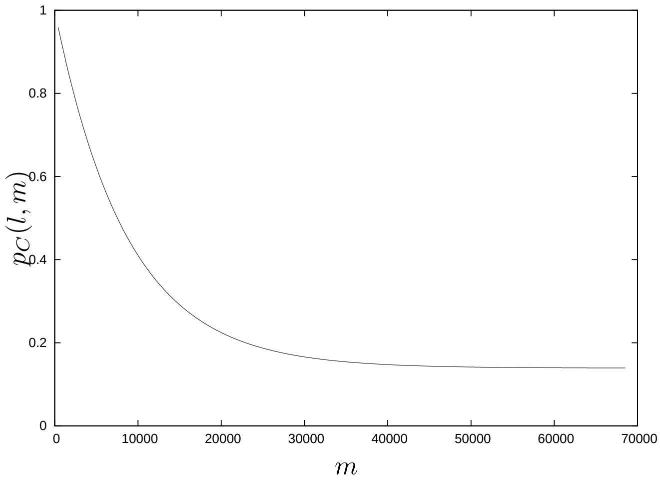

Fig. 2. Conditional probability that a packet transmitted at time m is erroneous given that a packet transmitted at 0 is erroneous ($l = 416$, $t = 0$, $p = 1$, $E[H_0] = 65.000$ bits, $E[H_1] = 10.000$ bits)

The protocol prescribes that R copies are transmitted over a single antenna, and the MS has to receive at least one of them. The first copy is transmitted over a steady-state Gilbert-Elliot channel and fails with probability $p_S(l)$. The second copy is transmitted immediately after the first one. Since it is transmitted over the same channel, the second packet fails with the conditional packet error probability $p_C(l,l)$ (here we have chosen $m = l$, since we assume the packets to be sent back-to-back). If the second packet is also erroneous, the third packet fails with probability

$$\begin{aligned}\Pr[T_{2l}(l) > t \,|T_l(l) > t] &= \Pr[T_l(l) > t \,|T_0(l) > t] \\ &= p_C(l,l)\end{aligned}$$

where we have used the time-homogeneity of the channel. Hence, we have:

$$p(R) = p_S(l)(p_C(l,l))^{R-1}$$

By similar arguments we conclude that for $R_S \neq 0$ we have:

$$p'(R) = p_S(l)(p_C(l,l))^{R_S-1}$$

otherwise, if $R_S = 0$ then $p'(R)$ should be set to one. We can express this as:

$$p'(R) = \mathbf{1}_0(R_S) + (1 - \mathbf{1}_0(R_S))p_S(l)(p_C(l,l))^{R_S-1}$$

where the function $\mathbf{1}_0(x)$ equals 1 for $x = 0$ and equals zero for $x \neq 0$.

Putting everything together we have:

$$\begin{aligned}p_F(D) &= (p_S(l))^{K_1}(p_C(l,l))^{K_1(R-1)} \\ &\quad \cdot(\mathbf{1}_0(R_S) + (1 - \mathbf{1}_0(R_S))p_S(l)(p_C(l,l))^{R_S-1})\end{aligned}$$

2) Case 2: $K \cdot R < D$: This case is important, since the number of antennas K may be bounded by economic reasons.

During the first K trials each antenna transmits R copies of the same packet using K independent channels. Using the result from the preceding Section IV-C.1 these first K trials fail with the overall probability:

$$(p_S(l))^K(p_C(l,l))^{K(R-1)}$$

Now let us consider the case where the first round robin round expired without success and antenna 1 starts its second trial to transmit a batch of R copies. The first packet is not transmitted over a steady-state channel. Instead, we have to take into account that the last packet of antenna 1's first batch was transmitted erroneously. Hence, the first copy of the second batch is erroneous with probability:

$$\Pr\left[T_{KRl}(l) > t \,\middle|\, T_{(R-1)l}(l) > t\right] = p_C(l, ((K-1)R+1)l)$$

For the second, third, ..., R-th copy of the second batch the same considerations apply as outlined in the preceding Section IV-C.1. Hence, the overall probability that the second batch of antenna 1 fails is given by:

$$p_C(l, ((K-1)R+1)l)(p_C(l,l))^{R-1}$$

By the time-homogeneity and the Markov property the third, fourth, etc. batch of the first antenna are stochastic replicas of the second batch. The same arguments are true for the other antennas.

Now we can put everything together. We have K batches transmitted over independent channels (Bernoulli experiments) and $K_1 = \lfloor \frac{D-KR}{R} \rfloor$ full "retransmission" batches, i.e. those batches which are transmitted after a preceding batch over the same channel already failed. Furthermore there might be one "slack" batch of $R_S = D - R(K + K_1)$ packets, which fails with probability:

$$\mathbf{1}_0(R_S) + (1 - \mathbf{1}_0(R_S))p_C(l, ((K-1)R+1)l)(p_C(l,l))^{R_S-1}$$

The assignment of a failure probability of one for the case $R_S = 0$ was done to maintain a uniform representation in the overall formula for the failure probability, presented next.

By the independence of the channels the overall failure probability can be computed as:

$$\begin{aligned} p_F(D) = {} & (p_S(l))^K \cdot (p_C(l,l))^{K(R-1)} \\ & \cdot \left[p_C(l, ((K-1)R+1)l) \cdot (p_C(l,l))^{R-1}\right]^{\lfloor \frac{D-KR}{R} \rfloor} \\ & \cdot \left[\mathbf{1}_0(R_S) + (1 - \mathbf{1}_0(R_S)) \right. \\ & \quad \left. \cdot p_C(l, ((K-1)R+1)l)(p_C(l,l))^{R_S-1}\right] \end{aligned} \tag{1}$$

D. Consequences

We are already in the position to provide a first insight into the gain which can be obtained by adding a number M of antennas (for the case $K \cdot R < D$). Assume that $R = 1$ (see below why this is a reasonable assumption), and for simplicity we assume that the numbers K and $K+M$ divide D evenly ($M \in \mathbb{N}$), i.e. there are no slack batches to consider. For this special case Equation 1 reduces to (with a slight change in notation):

$$p_F(D, K) = (p_S(l))^K \cdot (p_C(l, Kl))^{D-K}$$

The reduction factor of the failure probability by adding M antennas is then given by:

$$\frac{p_F(D,K)}{p_F(D, K+M)} = \left(\frac{p_C(l, (K+M)l)}{p_S(l)}\right)^M \cdot \left(\frac{p_C(l, Kl)}{p_C(l, (K+M)l)}\right)^{D-K}$$

For a bursty channel it is reasonable to assume that the conditional packet error probability $p_C(l, (K+M)l)$ is larger than the steady state packet error probability $p_S(l)$. Furthermore, as we have seen in Section IV-B, for sufficiently high values of $p_{g,g}$ and $p_{b,b}$ the conditional packet error probability is for increasing m monotonically decreasing down to the steady-state packet error probability. Hence, it is also reasonable to assume that $p_C(l, (K+M)l) < p_C(l, Kl)$. Both conditions together show that adding antennas truly improves the reliability by reducing the failure probability.

We are also in the position to investigate the effect of increasing R (i.e. the number of copies) on the failure probability, while K and D are kept fixed. For simplicity we assume that the numbers $K \cdot R$

and $K \cdot (R+1)$ divide D evenly, such that again no slack batches have to be considered. For this case Equation 1 becomes:

$$\begin{aligned} p_F(D,R) = \\ & (p_S(l))^K \cdot (p_C(l,l))^{K(R-1)} \\ & \cdot (p_C(l,((K-1)R+1)l))^{\frac{D-KR}{R}} \cdot (p_C(l,l))^{\frac{(R-1)(D-KR)}{R}} \end{aligned}$$

Comparing $p_F(D,R)$ and $p_F(D,R+1)$ gives us after some algebra:

$$\begin{aligned} \frac{p_F(D,R)}{p_F(D,R+1)} = \\ & \left(\frac{p_C(l,((K-1)(R+1)+1)l)}{p_C(l,l)}\right)^{\frac{D}{R(R+1)}} \\ & \cdot \left(\frac{p_C(l,((K-1)R+1)l)}{p_C(l,((K-1)(R+1)+1)l)}\right)^{\frac{D-KR}{R}} \end{aligned}$$

For monotonically decreasing conditional packet error probability the first term is smaller than one, the second term is larger than one, i.e. it depends on the rate of decay whether the multicopy-ARQ approach gives gains. As an example, for the numerical values used in Figure 2 and Section V (where the channel stays in the same state for comparably long times) the multicopy-ARQ approach makes things worse, i.e. it is better to not use this approach and to increase the number of antennas instead. However, for channels where the bad state holding time is short and the good state holding time is long, this approach can give gains.

V. Simulation setup

We have implemented a simulation model of the system described in Section II using a commercial simulation library [39]. The simulation model was verified by code inspection, by careful analysis of generated event sequences and by successful comparison of the simulation results with results obtained from the analytical model, see Section VI-A.

The main performance measure of interest is the *failure probability* $p_F(D)$ for some prescribed deadline of D trials per request. All simulations were carried out such that a minimum of 10 million requests and a maximum of 100 million requests was transmitted. If in between these bounds the confidence interval for the failure probability is with 95% confidence smaller than 2% of the true value then the simulation is stopped. This high number of requests is needed to obtain statistically significant results for small failure probabilities in the range of $10^{-5} \ldots 10^{-6}$.

To evaluate the analytical model, a separate program in ANSI Common Lisp [40] was written. This language offers, amongst other features, integers of arbitrary precision. The analytical model gives meaningful results where simulation is likely to fail: in case of extremely low failure probabilities $\leq 10^{-6}$ prohibitively long simulation times would be needed to obtain statistically significant results.

A. Parameters

The simulator allows to vary the following parameters:

- K is the number of base station antennas (or tightly coupled base stations).
- l is the length of a packet in bits.
- D is the number of admissible trials before a packet of length l misses its deadline.
- p is the bit error probability during the bad state of the Gilbert-Elliot channel and the Semi-Markov channel.
- $p_{g,g}$, and $p_{b,b}$ describe the state transition probabilities of the Gilbert-Elliot channel and thus their (mean) state holding times and the steady state probabilities to find the system in either state.

Parameter	Value
packet length l	416 bits
bit rate b	1 Mbit/s
deadline D	10 packets
$p_{g,g}$(Gilbert-Elliot)	0.9999846153846 (corresponds to 65.000 bits)
$p_{b,b}$(Gilbert-Elliot)	0.9999 (corresponds to 10.000 bits)
CoV bad state holding times (Semi-Markov)	10
CoV good state holding times (Semi-Markov)	20

TABLE I

FIXED PARAMETERS FOR ALL EXPERIMENTS (COV = COEFFICIENT OF VARIATION)

- b is the bit rate.
- ω is the interarrival time of requests at the central station. The requests are assumed to arrive periodically.

It is appropriate to fix some parameters in advance. The bit rate b is 1 Mbit/s. On each channel C_i runs a separate and independent instance of a channel error model (Gilbert-Elliot or Semi-Markov). For all channels the mean bad burst length is set to 10 ms (corresponding to 10.000 bits), and the mean good burst length to 65 ms (corresponding to 65.000 bits). These mean burst lengths are similar to those used in [41], which in turn were derived using a methodology described in [42], where the parameters of a N-state Markovian channel model are derived from some simple physical parameters like wavelength, Doppler frequency etc. These numbers lead to a rather bad channel: the steady-state probability π_1 for finding the channel in bad state is approximately 13.3%. For the Semi-Markov model we have chosen the mean good and bad burst lengths the same as for the Gilbert-Elliot model. However, inspired by the results of the measurement study [30] we set the coefficient of variation for the bad state holding times to 10, and for the good state to 20. This means that the channel state holding times are much more variable, with longer holding times occuring with higher probability than for the Gilbert-Elliot model, which has coefficients of variation below one.

The packet length l was set to 416 bits, corresponding to the 192 μs PHY header of an IEEE 802.11 compliant radio modem with DSSS PHY, plus eight bytes MAC header, plus 20 bytes user data, FEC overhead bits and checksum. PHY header bits, MAC header bits and user data bits are treated in the same way.[5] The deadline was set to a maximum of $D = 10$ trials, higher numbers need unacceptable simulation runtimes to achieve a certain accuracy. The fixed parameters are summarized in Table I, the other parameters were varied according to the needs of different experiments.

VI. RESULTS

We present the results for different simulation experiments.

A. Experiment: comparison of analytical model and simulation model

The first experiment is carried out to show the close correspondence between the analytical model and the simulation model under steady-state conditions. As channel model only the Gilbert-Elliot model is used. In the simulation the requests have a large interarrival time of 40 seconds in order to find the channel back in steady-state conditions when the next request arrives. We have simulated only for $t = 0$ and $t = 1$, since for higher values of t there are not sufficient failure events to make statistically meaningful statements. The variable parameters are summarized in Table II. Having both models showing similar results is important for *verifying* the simulation model and to trust its results when applied to more complex channel models.

[5]This assumption is inaccurate with respect to the PHY header, whichs main purpose is to allow the receiver to acquire bit synchronisation. Hence, it is not appropriate to talk about bit errors here, since the receiver has no access to single bits during the PHY header.

Parameter	Value
# of antennas K	1, 2, 3
# of correctable errors t	0, 1
interarrival time ω	40 s
error models	Gilbert-Elliot ($p \in \{1, 0.1, 0.01, 0.005, 0.001\}$

TABLE II

PARAMETERS FOR EXPERIMENT "COMPARISON OF ANALYTICAL AND SIMULATION MODEL"

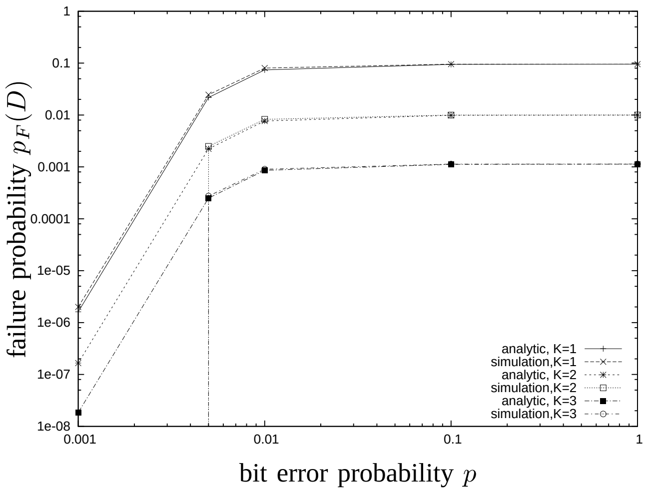

Fig. 3. Failure Probabilities vs. bit error probability p during bad state for the experiment "Comparison of Analytical and Simulation Model", $t = 0$

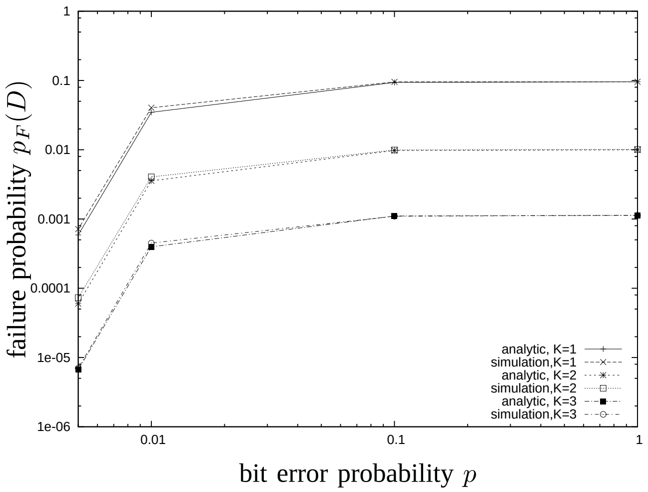

Fig. 4. Failure Probabilities vs. bit error probability p during bad state for the experiment "Comparison of Analytical and Simulation Model", $t = 1$

Parameter	Value
# of antennas K	1, 3, 5
# of correctable errors t	0, 2
error models	Gilbert-Elliot ($p \in \{1, 0.5, 0.1, 0.05, 0.01, 0.005, 0.001\}$

TABLE III
PARAMETERS FOR EXPERIMENT "EFFICIENCY OF REDUNDANCY APPROACHES"

In Figure 3 we show the failure probability $p_F(D)$ vs. the bit error probability in the bad state p for the case of $t = 0$, while Figure 4 displays the same for $t = 1$. The latter Figure 4 does not show the results for $p = 0.001$ since the simulation showed no failures during 10 million requests and the failure probability predicted by the analytical model is $< 10^{-12}$. The simulation values for $p = 0.001$ in Figure 3 are zero for $K = 2$ and $K = 3$, which matches the analytical results: for $t = 0$ and $K = 2$ the failure probability is $\approx 1.6 \cdot 10^{-7}$, for $K = 3$ it is $\approx 1.8 \cdot 10^{-8}$. Furthermore, without showing the results here, for $t > 1$ the simulation results and the analytical results match very well in those cases where the simulation gives nonzero values. We conclude that the analytical model and the simulation model match very well and the simulation model passes this verifi cation.

B. Experiment: efficiency of the redundancy approaches

In this experiment we use the analytical model to assess the relative influence of K and t when both are varied. The number of back-to-back copies R is set to one, inspired by the results from Section IV-D. The parameters K and t as well as the bit error probability p during the bad channel state (Gilbert-Elliot model) were varied according to the values given in Table III. In Figure 5 we show for the different values of K and t the failure probability $p_F(D)$ vs. the bit error probability p. The following points are remarkable:

- In any case, adding an antenna reduces the failure probability $p_F(D)$ by almost an order of magnitude.
- Using FEC starts to pay out when the bit error probability p is low enough to likely hit only a few bits within a packet. In the measurement study [30] we distinguished between bit errors and packet losses. Packet losses could be explained by the receiver not acquiring bit synchronisation. In case of packet losses FEC would be of no help, since utilizing the overhead bits already assumes to have bit synchronization. If we identify here the case of high bit error rates ($p = 0.1, p = 1$) with packet losses, and furthermore consider the observation that the bit error rates in the remaining packets were in the range $10^{-2} \ldots 10^{-3}$ at worst, we could recommend that adding antennas is the appropriate measure for combatting packet losses, while for combatting bit errors below a certain threshold FEC is much more effective. (Under the assumption that the primary goal is a reduction of the failure probability). For example: if we know beforehand that there are no packet losses and the bit error rate will not exceed $p = 0.001$, then for $t = 0$ and $K = 5$ we could achieve $p_F(D) \approx 10^{-9}$, while $t = 2$ and $K = 1$ gives $p_F(D) \approx 10^{-21}$.

C. Experiment: antenna redundancy over different channels

In this experiment we investigate by simulations the influence of antenna redundancy on the failure probability and the bandwidth need for the two different channel models, namely the Gilbert-Elliot model and the Semi-Markov model. In both models the error probability p during the bad channel state is set to one. The experiment is designed such that the requests have a large interarrival time ($\omega = 100$ seconds), which means that the next request hits the respective channels in steady-state conditions. The variable parameters of this experiment are summarized in Table IV. In this paper the bandwidth need is measured by the mean number of packets required to handle a request. Please note that we vary only the parameter K.

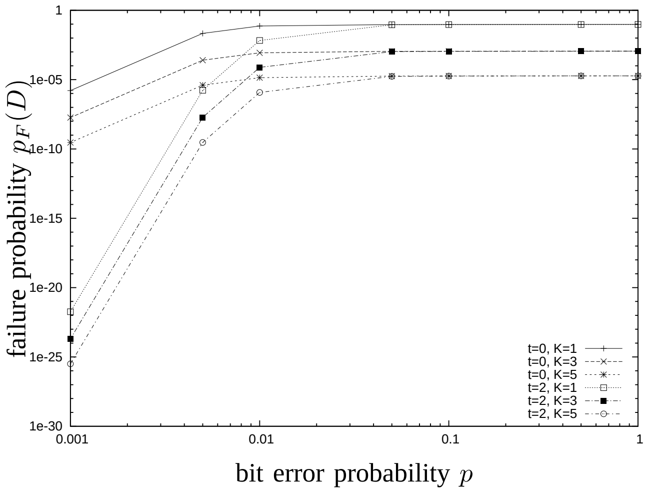

Fig. 5. Failure Probabilities vs. bit error probability p during bad state for the experiment "Efficiency of Redundancy Approaches", $t \in \{0, 2\}$

Parameter	Value
K	1, 2, 3, 4, 5, 6
interarrival time	100 s
error models	Gilbert-Elliot ($p = 1$), Semi-Markov ($p = 1$)

TABLE IV

PARAMETERS FOR EXPERIMENT "ANTENNA REDUNDANCY OVER DIFFERENT CHANNELS"

One important result is that for both error models each additional antenna buys approximately one order of magnitude lower failure probability, see Figure 6. Furthermore, $p_F(D)$ for the Semi-Markov channel is almost consistently higher than for the Gilbert-Elliot channel. An explanation for this is discussed in Section VI-D.

In Figure 7 we present the mean number of trials needed to handle a request vs. the number of antennas K. The mean number of trials reduces already significantly when adding a second antenna, the third and all further antennas show almost the same value. Therefore, already with the second antenna not only a reduced failure probability but also a reduced bandwidth need can be reached. The bandwidth reduction for increasing K can be explained by the fact that it takes longer before the base station is forced to return to an antenna which already experienced a transmission error and where it likely has to waste further bandwidth due to channel memory.

D. Experiment: effectiveness of the antenna-reuse policy

Finally, we present simulation results for the non-steady-state case: the interarrival times between requests are small enough that the channels could not expected to have reached the steady-state. Instead, each channel is likely correlated from request to request. The interarrival times chosen in this experiment are of practical interest for industrial applications: they are in the range of 5 to 30 milliseconds.

We additionally evaluate the *antenna reuse strategy*: in the original strategy described in Section II the central station starts each new request with antenna 1, while in the antenna reuse strategy it starts with the antenna where the last successful packet was transmitted. The effects of this strategy are evaluated for the two different channel error models. The variable parameters of this experiment are summarized in Table V.

In Figure 8 we show the failure probability for the two channel types and the two antenna reuse strategies. The following points are remarkable:

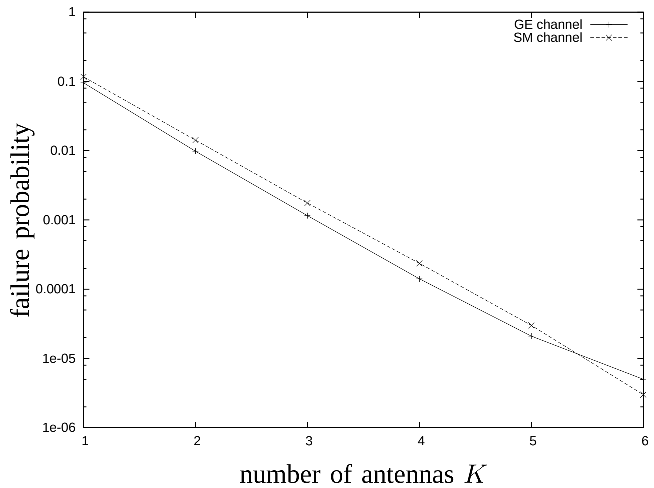

Fig. 6. Failure Probabilities for the experiment "effectiveness of antenna redundancy" for two different channel types

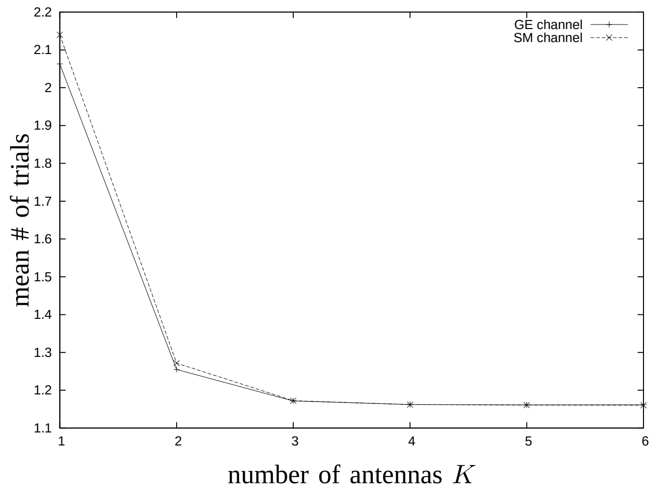

Fig. 7. Mean number of trials for the experiment "Antenna Redundancy over Different Channels"

Parameter	**Value**
K	3
interarrival time	5, 6, 7, 8, 9, 10, 12, 15, 20, 30, 40, 50 ms
error models	Gilbert-Elliot ($p = 1$), Semi-Markov ($p = 1$)
antenna reuse	yes, no

TABLE V

PARAMETERS FOR EXPERIMENT "EFFECTIVENESS OF THE ANTENNA REUSE POLICY"

	Gilbert-Elliot	**Semi-Markov**
# of failure bursts	17618	11552
mean failure burst length	1.2968554 requests	3.0114267 requests
product (= number of failures)	22848	34788

TABLE VI

COMPARISON OF FAILURE BURST STATISTICS FOR $l = 416$, $t = 0$, $R = 1$, $D = 10$, $K = 3$, $\omega = 5$ MILLISECONDS ARRIVAL PERIOD, WITHOUT ANTENNA REUSE AND 20 MILLION REQUESTS

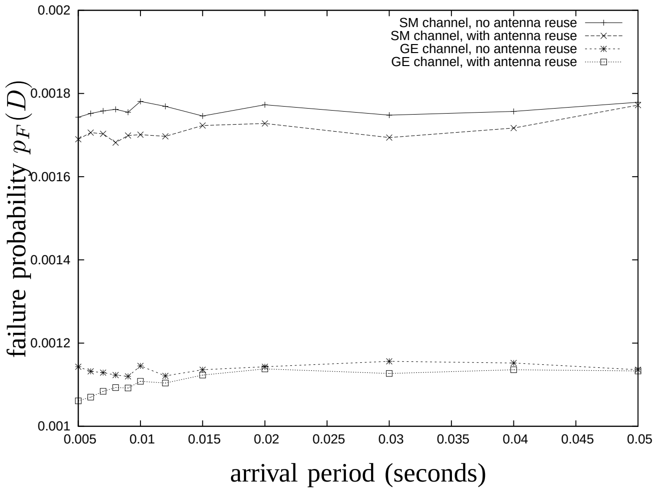

Fig. 8. Failure Probabilities for the experiment "effectiveness of antenna reuse policy" vs. arrival period ω for the two different channel types

- For both the Gilbert-Elliot model and the Semi-Markov model the failure probabilities are not sensitive against the arrival period. This is even true for the "steady-state" interarrival period of 100 seconds, which show almost identical results as for the much smaller arrival periods.
- The Semi-Markov model has significantly higher failure probabilities than the Gilbert-Elliot model (increased by more than 50%), hence, the increased variability reduces the system reliability. This can be explained as follows: the lognormal distributions used for the channel state holding times have comparably large coefficients of variation. The first packet of a request transmitted on one of the $K = 3$ channels corresponds to a random sampling during either a good or a bad channel state holding time. From renewal theory [43, Chapter 3] we know that in the steady state for an arbitrary interarrival time distribution X the expected value of the residual lifetime (here: the expected time to stay in the same state) is given by:
$$\frac{E\left[X^2\right]}{2E\left[X\right]}$$
which we can rewrite using the squared coefficient of variation $C_X^2 = \frac{\mathrm{Var}[X]}{(E[X])^2}$ as:
$$E\left[X\right] \cdot \frac{1 + C_X^2}{2}$$
The geometric distributions used in the Gilbert-Elliot model have a coefficient of variation smaller than one, while for the Semi-Markov model we have used much higher values. By the above formula, we have much higher expected residual lifetimes. This has the consequence that once a channel is found in the bad state, it will likely stay in this state for longer time than in the Gilbert-Elliot model. The same holds true for the good state holding times. If we denote successively failed requests as a *failure burst*, we compare in Table VI for a specific example the statistics of failure bursts for both the Gilbert-Elliot model and the Semi-Markov model, both taken for the same parameters and 20 million requests. It can be seen that the increased length of the failure bursts for the Semi-Markov channel outweighs their more rare occurence, which in turn explains the higher failure probability for the Semi-Markov model.
- For the Semi-Markov model the difference in the failure probabilities between the strategies with and without antenna reuse is statistically significant. It can be seen that the antenna reuse policy gives an (albeit small) reduction in the failure probability, while for the Gilbert-Elliot model the differences tend to become small for arrival periods larger than 10 milliseconds.

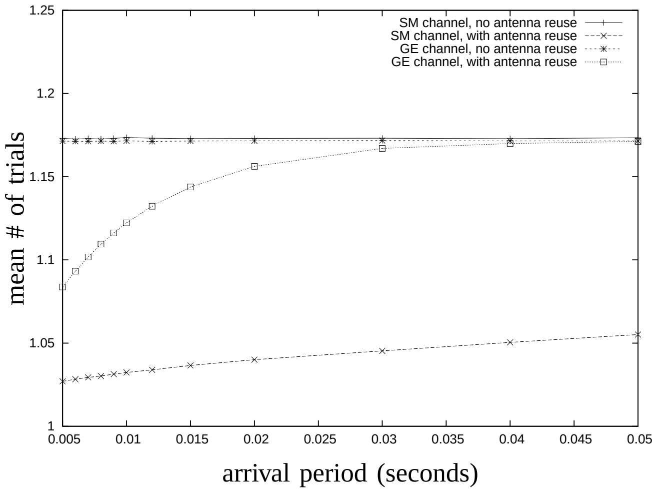

Fig. 9. Mean number of trials for the experiment "effectiveness of antenna reuse policy" for two different channel types

In Figure 9 we show the mean number of packets needed to handle a request until it is successful or reaches its deadline. Two conclusions can be drawn:

- For both channel error models the strategies without antenna reuse deliver almost the same performance, and in both cases the antenna reuse scheme gives a real gain in the number of packets / bandwidth needed to handle a request. However, in both cases the gain decreases for increasing arrival period, until eventually the antenna reuse strategy gives no gain over the scheme without antenna reuse.
- The larger variability of the channel state holding times for the Semi-Markov model makes the antenna reuse strategy much more effective than for the Gilbert-Elliot model. As stated above, once the channel is in the good state (as is typically the case for the last successful packet of the preceding request) it can be expected to stay here for much longer time as for the Gilbert-Elliot channel. Hence, the next packet on this channel (aka: the first packet of the next request) is more likely to succeed and to reduce the number of packets needed to handle the next request to one.

To summarize, for small interarrival times and channels with some memory (like the Gilbert-Elliot and Semi-Markov channels) the antenna reuse strategy reduces the failure probabilities only by a small amount, but it reduces the mean number of packets needed to transmit a request significantly, which saves bandwidth and power.

VII. CONCLUSIONS

This paper has explored the capabilities of different kinds of redundancy to reduce the failure probability, i.e. the probability to miss an important deadline. This probability is of utmost importance for the application of wireless LAN technology in industrial environments. We have investigated three different kinds of redundancy: the well-known FEC and multicopy-ARQ approaches, and antenna redundancy. Antenna redundancy explores the advantages of spatial transmitter diversity (and of receiver diversity in the case of packets sent from the wireless station to the central station) while keeping the complexity of the receiver low, as compared to true transmit diversity/MIMO systems. This makes the implementation of antenna redundancy attractive in scenarios where the mobile / wireless stations are small and cheap field devices (for example sensors)

For the case of independent (and rather bad) channels between the antennas and a mobile station the antenna redundancy approach decreases the failure probability by almost one order of magnitude per additional antenna. Furthermore, already for the second antenna we achieve a significant reduction in the mean number of packets needed to handle a request; using the antenna reuse strategy can give further bandwidth savings for request interarrival times of practical interest (millisecond range). These savings can be used to meanwhile serve other mobile stations. As compared to FEC the antenna redundancy approach is most effective w.r.t. failure probability when the error rates are high or the channel shows packet losses, while FEC gives larger gains when the error rates are low enough to distort only a few bits per packet. The multicopy-ARQ approach does not behave well over the kind of channels used in this paper.

To conclude the paper we discuss possible research directions, both theoretical and practical. The aspect of channel models and their influence on the reduction in failure probability the antenna redundancy approach can achieve offers several opportunities for theoretical work. In fact, in this paper we have used quite an idealized channel model for evaluating the antenna redundancy approach: the channels are independent and follow the same stochastic process. Neither of these assumptions will be true in practice and the question comes up how much can still be gained with antenna redundancy in terms of failure probability when these assumptions are removed. If we assume that all channel error processes are driven by the same stochastic model but allow for some correlation between the channels, then we can ask how the achievable gains in terms of failure probability depend on the degree of correlation between channels. If we allow heterogeneous channels then strategies to treat the channels differently become interesting: if one channel stays in bad state for long time then it should be less frequently chosen for performing retransmissions, and better channels should be favored. Another restriction of this paper with respect to channel modeling is the complexity of a single channel: neither the issue of packet losses nor the influence of state holding time distributions with very large variability or even heavy-tailed distributions have been assessed so far.

There are also several more practical aspects deserving attention in the future. One interesting topic is adaptivity: in practical applications the channel statistics are time-variable and not known in advance, so any fixed choice of the parameters K, t and R will not always be optimal. Therefore, methods for estimating the channel state and for sensible adaptation of t and R are interesting (K will be fixed at configuration time). Another worthwhile question is how the techniques described in this paper can be applied to commercial wireless LAN technologies, for example the IEEE 802.11 family.

ACKNOWLEDGEMENTS

The author wishes to thank the anonymous reviewers for their helpful comments.

APPENDIX A: EXACT SOLUTION FOR THE STEADY-STATE PACKET ERROR PROBABILITY OVER A GILBERT-ELLIOT CHANNEL

We are given a Gilbert-Elliot channel in steady-state, however, for notational convenience we assume to start at time 0, i.e. the states of the channel are given as $X_0, X_1, X_2, \ldots$. The steady-state assumption implies that $\Pr[X_0 = 0] = \pi_0$ and $\Pr[X_0 = 1] = \pi_1$. We introduce the random variable $T_i(l)$, denoting the number of bit errors which occur in a packet of length l bits, when its transmission is started at time X_i. Furthermore, let $p_S(l)$ denote the probability that a packet of length l bits transmitted over the steady-state Gilbert-Elliot channel at time X_0 is erroneous, i.e. has more than the t bit errors that can be corrected by the FEC code. We can thus express $p_S(l)$ as:

$$p_S(l) = \sum_{n=t+1}^{l} \Pr[T_0(l) = n]$$

We can express $\Pr[T_0(l) = n]$ by conditioning over the number of bits which are in bad state during the packet transmission time:

$$\begin{aligned} \Pr[T_0(l) = n] &= \sum_{m=n}^{l} b(n; m, p) \cdot \Pr[m \text{ out of } l \text{ bits in bad state}] \\ &=: \sum_{m=n}^{l} b(n; m, p) \cdot \Pr[B_0(l) = m] \end{aligned}$$

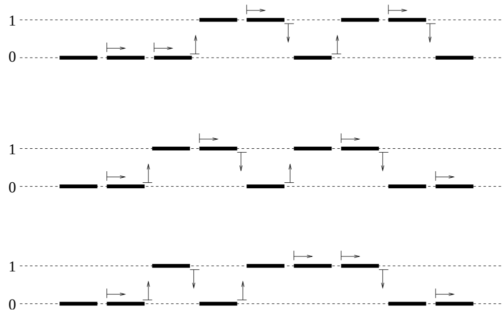

Fig. 10. Two different outcomes with $l = 9$ and $m = 4$

where $b(n;m,p) = \binom{n}{k} p^k (1-p)^{n-k}$ is the binomial distribution and $\Pr[B_i(l) = m]$ is the probability that a packet of length l bits started at time i is in the bad state for exactly m bits over its duration. This expression results from the assumption that during bad states bit errors occur according to independent Bernoulli experiments with probability p.

The tricky part is to find $\Pr[B_i(l) = m]$, since the number of bursts and their respective lengths during a packet can be arbitrary, as long as the sum of the burst lengths is just m. We illustrate our approach by help of an example, shown in Figure 10 for the special case of having $m = 4$ error states during $l = 9$ bits. The good state is marked with a “low” line segment, and the bad state with a “high” line segment. Due to the Markov property of the channel TH-DTMC we can compute the probability for the upper sequence as:

$$\begin{aligned}
&\Pr[X_0 = 0] \cdot \Pr[X_1 = 0 \,|X_0 = 0] \cdot \Pr[X_2 = 0 \,|X_1 = 0] \cdot \Pr[X_3 = 1 \,|X_2 = 0] \\
&\cdot \Pr[X_4 = 1 \,|X_3 = 1] \cdot \Pr[X_5 = 0 \,|X_4 = 1] \cdot \Pr[X_6 = 1 \,|X_5 = 0] \\
&\cdot \Pr[X_7 = 1 \,|X_6 = 1] \cdot \Pr[X_8 = 0 \,|X_7 = 1]
\end{aligned}$$

which, by the time-homogeneity of $\mathbf{P}$ and with introducing the shorthand $p_{i,j} = \Pr[X_1 = j \,|X_0 = i]$ is the same as:

$$\begin{aligned}
& \Pr[X_0 = 0] \cdot p_{0,0} \cdot p_{0,0} \cdot p_{0,1} \cdot p_{1,1} \cdot p_{1,0} \cdot p_{0,1} \cdot p_{1,1} \cdot p_{1,0} \\
= \quad & \Pr[X_0 = 0] \cdot p_{0,0}^{N_{0,0}} \cdot p_{0,1}^{N_{0,1}} \cdot p_{1,1}^{N_{1,1}} \cdot p_{1,0}^{N_{1,0}}
\end{aligned}$$

It is noteworthy that the two lower example sequences of Figure 10 have the same probability. We can observe that for all three example sequence the following holds: we have $N_{0,1} = 2$, and since we start and end with a good state, it follows that $N_{1,0} = N_{0,1} = 2$. Since we also must have that $m = N_{0,1} + N_{1,1}$ we can express $N_{1,1}$ also in terms of $N_{0,1}$ as $N_{1,1} = m - N_{0,1}$. Finally, with $X_0 = 0$ given, the number $N_{0,0}$ is given as $N_{0,0} = l - m - N_{0,1} - 1$. Therefore, the numbers $N_{0,0}$, $N_{1,1}$, and $N_{1,0}$ can be expressed in terms of l, m and $N_{0,1}$. Consequently, all sequences $X_0, \ldots, X_8$ starting and ending with good states and having two “rising edges” (going from state 0 to state 1) have the same probability. Therefore, we need “only” to count the number of such sequences. Be $C_{0,0}(l, m, u)$ be the number of sequences where m bits are in bad state for a packet of length $l \geq 2$ bits, such that we have u rising edges and the first as well as the last bit are in good state. Therefore, be $l \geq 3$ and $0 \leq m \leq l - 2$ the number of bits in bad state during the l bits of the packet. If the number of rising edges u is zero, we have:

$$\begin{aligned}
C_{0,0}(l, 0, 0) &= 1 \\
C_{0,0}(l, m, 0) &= 0 \quad (\text{for } m > 0)
\end{aligned}$$

because there is only a single sequence with zero errors in l bits, and there are no sequences where we have $m > 0$ errors but no rising edges; the all-errors sequence would require $X_0 = 1$ and $X_{l-1} = 1$. Next consider $u = 1$ and an overall of m bits in bad state. Consequently, these bits must be contiguous and the number possibilities to place m bad bits in a packet of l bits starting with a good and a bad bit is:

$$C_{0,0}(l, m, 1) = l - m - 1$$

For higher numbers of rising edges u we can separate the first burst of $m\prime$ bits length, which occurs at position k and ends at position $k+m' - 1$ and is by its definition followed by one good bit. There are then $C_{0,0}(l - (m' + k), m - m', u - 1)$ ways to distribute the remaining $m - m'$ bad states over the remaining $l - (m' + k)$ bits by using $u - 1$ rising edges. Considering all possible burst lengths m' of the first burst and all possible start positions we have:

$$C_{0,0}(l, m, u) = \sum_{m'=1}^{m-u+1} \sum_{k=1}^{l-m-u} C_{0,0}(l - (m' + k), m - m', u - 1)$$

One can now prove inductively that this recursive equation can be turned into an explicit representation:

$$C_{0,0}(l, m, u) = \frac{1}{u!\,(u-1)!} \cdot \frac{(m-1)!}{(m-u)!} \cdot \frac{(l-m-1)!}{(l-m-1-u)!}$$

which holds for $l \geq 3$, $1 \leq m \leq l - 2$ and $m + u \leq l - 1$; for parameters not satisfying these constraints $C_{0,0}(l, m, u) = 0$.

How about those cases where the packet starts with a good state but ends with a bad state or where the packet starts in bad state? Consider first the case where the packet starts in bad state and ends in good state. We can enumerate the different possible lengths for the first error burst (including the first bit) and can use our previous results to distribute u bursts over the remaining bits, which by definition start with the good bit following the first burst and end with a good bit. Therefore, we have:

$$\begin{aligned} C_{1,0}(l, m, 0) &= 1 \\ C_{1,0}(l, m, u) &= \sum_{m'=1}^{m-u} C_{0,0}(l - m', m - m', u) \end{aligned}$$

subject to the constraints $l \geq 2$, $m \leq l - 1$, and $m + u \leq l - 1$. Similarly:

$$\begin{aligned} C_{0,1}(l, m, 0) &= 0 \\ C_{0,1}(l, m, 1) &= 1 \\ C_{0,1}(l, m, u) &= \sum_{m'=1}^{m-u+1} C_{0,0}(l - m', m - m', u - 1) \end{aligned}$$

and finally, for the number of outcomes starting and ending with a bad state we have:

$$\begin{aligned} C_{1,1}(l, m, 0) &= 1 \\ C_{1,1}(l, m, u) &= \sum_{m'=1} m - u C_{0,1}(l - m', m - m', u) \end{aligned}$$

Putting everything together, we can express $\Pr\left[B_0(l)=m\right]$ as:

$$\begin{aligned}\Pr\left[B_0(l)=0\right] &= \Pr\left[X_0=0\right]\cdot p_{0,0}^{l-1}\\ \Pr\left[B_0(l)=m\right] &= \Pr\left[X_0=0\right]\cdot\\ &\Big(\sum_{u=1}^{m} C_{0,0}(l,m,u)\cdot p_{0,1}^{u}\cdot p_{1,0}^{u}\cdot p_{1,1}^{m-u}\cdot p_{0,0}^{l-m-u-1}\\ &+\sum_{u=1}^{m} C_{0,1}(l,m,u)\cdot p_{0,1}^{u}\cdot p_{1,0}^{u-1}\cdot p_{1,1}^{m-u}\cdot p_{0,0}^{l-m-u}\Big)\\ &+\Pr\left[X_0=1\right]\cdot\\ &\Big(\sum_{u=1}^{m} C_{1,0}(l,m,u)\cdot p_{0,1}^{u}\cdot p_{1,0}^{u+1}\cdot p_{1,1}^{m-u-1}\cdot p_{0,0}^{l-m-u-1}\\ &+\sum_{u=1}^{m} C_{1,1}(l,m,u)\cdot p_{0,1}^{u}\cdot p_{1,0}^{u}\cdot p_{1,1}^{m-u-1}\cdot p_{0,0}^{l-m-u}\Big)\end{aligned}$$

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