Redundancy Concepts to Increase Transmission Reliability in Wireless Industrial LANs

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***Abstract*—Wireless LANs are an attractive networking technology for industrial applications. A major obstacle toward the fulfillment of hard real-time requirements is the error-prone behavior of wireless channels. A common approach to increase the probability of a message being transmitted successfully before a prescribed deadline is to use feedback from the receiver and subsequent retransmissions (automatic repeat request—ARQ—protocols). In this paper, three modifications to an ARQ protocol are investigated. As one of these modifications a specific transmit diversity scheme, called antenna redundancy, is introduced. The other modifications are error-correcting codes and the transmission of multiple copies of the same packet. In antenna redundancy the base station/access point has several antennas. The base station transmits on one antenna at a time, but whenever a retransmission is needed, the base station switches to another antenna. The relative benefits of using FEC versus adding antennas versus sending multiple copies are investigated under different error conditions. One important result is that for independent Gilbert–Elliot channels between the base station antennas and the wireless station the antenna redundancy scheme effectively decreases the probability of missing a deadline, in a numerical example approximately an order of magnitude per additional antenna can be observed. As a second benefit, antenna redundancy decreases the number of transmission trials needed to transmit a message successfully, thus saving bandwidth.**

***Index Terms*—Antenna redundancy, antenna reuse strategy, FEC, multicopy-ARQ, redundancy, wireless industrial LANs.**

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]–[4]. Wireless links are prone to possible transmission errors caused by deep fades (which occur when the received signal strength drops below a critical threshold) or interference. A number of measurement studies has revealed time-variable and sometimes quite high error rates, see for example [5]–[7] reporting measurements with IEEE 802.11/11b-compliant chipsets. One of the central problems in the design of wireless industrial communications systems is that the real-time and reliability requirements found in these systems are more likely to be jeopardized over wireless channels than they would be over a wired channel. Accordingly, there is significant interest in mechanisms which make transmission over wireless channels more robust. Since it is practically impossible to *guarantee* delivery of packets within prescribed deadlines over error-prone wireless links, the goal of such mechanisms is to increase the *probability* of correct and deadline-preserving packet delivery. For industrial applications, often much higher delivery probability levels are required than for "soft" real-time traffic like interactive voice or video. One strategy to improve transmission robustness is to improve the lower layer protocols, namely the medium access control (MAC) and link-layer protocols. This paper adopts this strategy.

Specifically, we look at the task of transmitting a packet from a base station/access point to a wireless station within a prescribed deadline. The packet is equipped with a checksum and the wireless station can provide the base station with feedback upon proper reception of the packet. In case of negative feedback, the base station retransmits the packet until it is correctly received (the base station receives positive feedback), or the packet deadline has expired. This mode of operation involving receiver feedback and retransmissions is at the heart of Automatic Repeat reQuest (ARQ) protocols [8]. When a packet deadline expires, the base station drops the packet and we have a *failure* situation. The main performance measure investigated in this paper is the *failure probability*, i.e., the probability that a packet cannot be transmitted successfully before its deadline. To reduce the failure probability, we consider different modifications of ARQ protocols.

- The base station may use additional forward error correction (FEC) coding. In FEC schemes [9], the transmitter adds redundant bits to a packet which allow the receiver to correct bit errors if there are not too many of them.
- The base station can transmit a packet not only once but multiple times in a *batch*, and the receiver provides negative feedback only if it fails to receive any of these copies. This is called multicopy-ARQ [10].
- The base station can use a different spatial channel for a retransmission. The particular scheme used to achieve this, the *antenna redundancy* scheme, is one of the contributions of this paper.

As a second contribution, in this paper a combined ARQ protocol is described, which can involve mixtures of these three modifications. The relative benefits of these modifications in terms of failure probability reduction over different types of wireless channels are investigated using analytical and simulation modeling of the combined ARQ protocol.

The approach to use different spatial channels has its grounds in the observation that the signal seen at a receiver is a superposition of many signal components, for example a line-of-sight component and a number of delayed signal components created by reflection, diffraction or scattering of wireless waveforms.

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These superposed signal components interfere with each other at the receiver. In case of destructive interference, the overall received signal may be too weak to be detected properly by the receiver, this is called a *deep fade*. A change in the receiver's position can change the number and relative delay of signal components. Consider two receiver positions r and s, which have the same distance to a transmitter. If r and s are relatively close to each other, the probability that r and s experience a deep fade *at the same time* is higher than if their distance is larger than the so-called *coherence distance*—beyond this distance the signals at r and s are only weakly correlated.[1] Stated differently: if a station A transmits a packet to the distant stations B and C (having both the same distance to A), then it might well happen that B receives the packet correctly, while C experiences an error. The channel behavior is thus space-dependent (*spatial diversity*).

It has already been shown in [2] that spatial diversity can be used to improve the probability that a packet can be successfully transmitted before its deadline. The schemes developed in [2] make use of a *third* station besides transmitter and receiver. Specifically, when station A fails to transmit a packet to station C, another station B might have picked up the packet and perform the retransmission on behalf of A. Such schemes provide a kind of *cooperative diversity* [13]. This kind of spatial channel switching is helpful when the average duration of a deep fade on a channel is longer than the packet duration: when a packet on one spatial channel fails, probably an *immediate* retransmission over the same channel will fail, too, because the retransmitted packet can be hit by the same deep fade. Therefore, it might be advantageous to switch to another spatial channel. Error bursts on wireless channels, for example, often last some tens of milliseconds, which would cover multiple subsequent packets.

The *antenna redundancy* scheme introduced in this paper also exploits spatial diversity, but differs from the schemes described in [2] in a very important respect: the schemes from [2] require a *third* station besides base station and wireless station to help with retransmissions, and the protocols running in all these three stations must include special protocol mechanisms to implement their cooperation. In contrast, antenna redundancy does not require a third station, and the protocol implementation in the wireless station does not need any extra mechanisms, which allows to use wireless stations in environments with and without antenna redundancy. In antenna redundancy, it is assumed that the base station has multiple antennas, having mutual distances larger than the coherence distance. Antenna redundancy thus belongs to the class of *transmit diversity* schemes [11, Ch. 7], like the Alamouti scheme [14] or MIMO (multiple input, multiple output) systems [15]. The Alamouti scheme uses two transmit antennas, a single receive antenna and works on the level of individual channel symbols. Very briefly: a symbol is transmitted on one antenna, and one symbol time later it is repeated on the other antenna. It is shown in [14] that this scheme gives the same gains in symbol reception probability than receive diversity with two antennas at the receiver would do. MIMO systems [15] require multiple transmit and multiple receive antennas and use sophisticated coding and signal processing techniques to increase channel capacity over single receive/transmit antenna solutions. The Alamouti scheme cannot be implemented with commercially available networking cards, and MIMO techniques have high system costs due to their signal processing requirements. Furthermore, the need to carry multiple antennas requires larger form factors, which is not always desirable when small sensors are used as wireless devices.

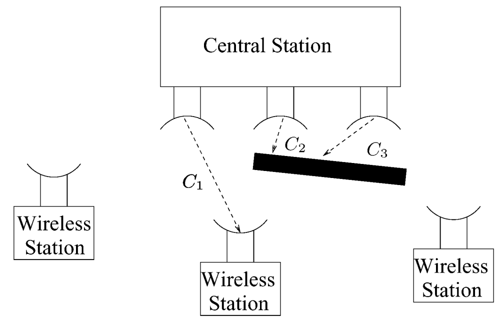

Fig. 1. Example scenario with a central station having three antennas, three wireless stations and an obstacle.

In contrast, antenna redundancy does not work on a symbol-by-symbol, but on a packet-by-packet basis. 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. 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 spaced appropriately, a wireless station separated by an obstacle from some antennas might still be in reach of other antennas (compare Fig. 1). As compared to the Alamouti scheme and MIMO systems, this approach does not require additional signal processing or multiple antennas at the receiver, and can be readily implemented with commercially available equipment. This allows to keep wireless stations simple and cheap (think of small sensors and actuators), the additional complexity is placed into the base station. To the best of my knowledge this scheme has not been suggested before.

In this paper, an analytical and simulation-based evaluation of the combined ARQ protocol's failure probability is carried out, considering 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 on 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 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 [18]. The semi-Markov model is a generalization of the Gilbert–Elliot model, giving greater flexibility in modeling the duration of channel

[1]This *coherence distance* depends, among other parameters, on the antenna type and the propagation environment [11, Sec. 5.8.5], [12]. When signal components can arrive from every direction, for example, a spacing between half a wavelength and a full wavelength is sufficient to achieve diversity gains (compare [12]).

fades. The results obtained from the analytical Gilbert–Elliot model and the simulation model match well. This validates the simulation model and makes results for other channel models 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 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. It is shown that, using the antenna reuse policy, 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 relevant 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 developed models allow to explore the different tradeoffs and to find good solutions for known channel conditions.

This paper is structured as follows. In Section II, we explain in greater detail the system model and the combined ARQ scheme including 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 and semi-Markov channel models. In Section IV we present the analytical model for the failure probability of the combined ARQ scheme when operated over a Gilbert–Elliot channel. After discussing the simulation setup (Section V), we present the results of simulations and analytical evaluations in Section VI. Finally, in Section VII, we give our conclusions and discuss future research directions.

Some of the results in this paper were already presented in [19]. Due to lack of space, some derivations and results are omitted in this paper, but can be found in [20].

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 larger than the coherence distance. We focus on a single wireless station (WS). There is a separate wireless channel between the WS and each antenna (see Fig. 1); the channel between antenna i and the WS 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 and if the antennas are spaced apart more than the coherence distance. We make the strong assumption of independence because of its theoretical utility. If the error behavior would be dominated by interference (e.g., the WS is located close to a microwave oven), then different channels would probably show strongly correlated error behavior and the analysis developed below must be modified.

The combined ARQ scheme operates as follows. We denote as a *request* a piece of data which has to be transmitted within a prescribed deadline from the central station to wireless station (WS). This piece of data is encapsulated into a *packet*, which includes a checksum. When FEC is enabled, the packet is coded according to an (assumed optimal) FEC scheme capable of correcting up to $t \geq 0$ errors. The final packet has a size of l bits. The following procedure (based on the stop-and-wait protocol) is used to handle a request: for the first trial the central station transmits a batch of $R \geq 1$ identical copies of the final packet over antenna 1. For this multicopy-approach to work correctly, the packets must carry sequence numbers which allow the receiver to identify duplicates. When the WS receives any of the R packets correctly, it sends an acknowledgment (ack) frame. We assume the ack to be transmitted in zero time and error-free. If the central station receives no ack, it uses antenna 2 for the second trial, again transmitting a batch of R copies of the packet. 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, one of the packets was successfully received by the WS and we have a *success*. The *deadline* d is defined as follows:

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

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.

Using a FEC scheme has not only advantages: its overhead makes packets longer or reduces the bandwidth available to the user when the final packet size is to be kept fixed. The overhead is expended even during good channel periods. On the other hand, 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 by the packet checksum.

In the antenna redundancy approach with K antennas, a packet/batch directed from the central station to the WS 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

[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.

received or the deadline 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 reused. It is important to note that the receiving WS needs only a single antenna and can be kept simple. In the uplink direction the K antennas provide *receiver diversity* [11, Ch. 7]. 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. However, we do not consider this any more in this paper.

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 [21] is an attractive choice. Several measurement studies investigate the error behavior of IEEE 802.11-compliant radio modems in different environments (e.g., [5]–[7]), some of them in industrial environments ([5]). These measurements showed some characteristics which we take as basis and motivation for this work: 1) time-varying behavior; 2) large variance in the distributions of the lengths of error bursts and error-free periods (called *runs*); bursty errors/long-lasting correlation; and 3) sometimes high bit error rates up to $10^{-3}\ldots10^{-2}$. 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.

In this paper we focus on two different models: the popular *Gilbert–Elliot model* and a *Semi-Markov model*, which is a variation of the Gilbert–Elliot model.

A. 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. The Gilbert–Elliot model is a two-state time-homogeneous discrete time Markov chain (TH-DTMC). The model works with slotted 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. The parameter of this experiment 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

$$\pi_0 = \frac{1-p_{b,b}}{2-(p_{g,g}+p_{b,b})}, \quad \pi_1 = \frac{1-p_{g,g}}{2-(p_{g,g}+p_{b,b})}.$$

It is shown in [20] that autocorrelation between the channel at time s and the channel at time $s+t$ decays exponentially. The channel has thus only a short-term memory.

The state holding times are geometrically distributed and hence are *memoryless*.[3] 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

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

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.

B. 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 WS 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

[3]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.

express bursty channel behavior (Section IV-A). Two different cases are investigated: a) packet transmission when the channel is in the steady-state 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. 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-B).

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

A. Packet Error Probabilities 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

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

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

$$\begin{aligned} \Pr[X_0 = 0] = \pi_0 &= \frac{1 - p_{b,b}}{2 - (p_{g,g} + p_{b,b})} \\ \Pr[X_0 = 1] = \pi_1 &= \frac{1 - p_{g,g}}{2 - (p_{g,g} + p_{b,b})}. \end{aligned}$$

We are now faced to the calculation of $\Pr[T_0(l) = n | X_0 = 0]$ and $\Pr[T_0(l) = n | X_0 = 1]$. Appropriate expressions are derived in [20] under the assumption of having at most one state transition (from good to bad channel state or vice versa) in a single packet. Specifically, under this assumption one obtains:

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

where $b(k; n, p) = \binom{n}{k} p^k (1-p)^{n-k}$ is the binomial distribution. Furthermore

$$\begin{aligned} \Pr[T_0(l) = n | X_0 = 1] = \sum_{k=n}^{l-1} b(n; k, p)(1 - p_{b,b}){p_{b,b}}^{k-1} \\ + b(n; l, p){p_{b,b}}^l. \end{aligned}$$

The 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.

Precisely, we are interested in calculating the probability

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

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. Using again the assumption that at most one channel state change occurs within a packet, it is derived in [20] that $\Pr[T_m(l) = n]$ can be expressed as

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

where $p_{l,0}$ is a shorthand for

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

and $[[\mathbf{P}^k]]_{i,j}$ is the i,jth component of matrix $\mathbf{P}^k$. A numerical example discussed in [20] shows that $p_C(l, m)$ is indeed for small m larger than the steady-state probability $p_S(l)$. However, for increasing m the probability $p_C(l, m)$ converges to $p_S(l)$.

B. Failure Probability for K Antennas With Round-Robin

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 WS. There are $K_1 := \lfloor D/R \rfloor$ 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 $R_S := D \bmod R$ 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.

The protocol prescribes that R copies are transmitted over a single antenna, and the WS 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

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

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 Section IV-B1, 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

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

For the second, third, …, Rth copy of the second batch the same considerations apply as outlined in Section IV-B1. 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 memoryless 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 $K_1 = \lfloor D - KR/R \rfloor$ 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

$$\begin{aligned}&\mathbf{1}_0(R_S) + (1 - \mathbf{1}_0(R_S))\\ &\qquad \times p_C(l, ((K-1)R+1)l)(p_C(l,l))^{R_S-1}.\end{aligned}$$

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

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

C. 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 to the K antennas that are already present. We assume that $R = 1$ (see below why this is a reasonable assumption), $K + M < D$, 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 (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

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

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, it is shown in [20] that for sufficiently large values of $p_{g,g}$ and $p_{b,b}$ (leading to long average state holding times), the conditional packet error probability decreases monotonically down to the steady-state packet error probability, as m is increased. 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.

Another interesting question concerns the effect of increasing the number of copies R. It is shown in [20] that for channels, which have large mean state holding times as compared to the packet length, choosing R larger than one actually *increases* the failure probability as compared to a setup with $R = 1$. An explanation is that during a deep fade likely the whole batch is lost, but the time needed to transmit this batch reduces the remaining time before the deadline expires by much more than a single packet would do.

V. Simulation Setup

We have implemented a simulation model of the system described in Section II using a commercial simulation library [22]. 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. In fact, an experiment reported in [20] shows quite satisfying correspondence between analytical results and the results obtained by simulation for a range of parameter settings.

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 $10^{-5} \ldots 10^{-6}$.

The analytical model is evaluated with a separate program written in ANSI Common Lisp [23]. Lisp offers, amongst others, integers of arbitrary precision. The analytical model gives meaningful results where simulation fails: for 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 a number of parameters. For the purposes of this paper, however, some of these parameters are set to fixed values. The fixed parameters are summarized in Table I, the other parameters were varied according to the needs of different experiments:

- K is the number of base station antennas.
- l is the length of a packet in bits. When no FEC coding is used ($t = 0$), the length l is fixed to $l = 416$ bits throughout this paper (see [20] for the factors contributing to this number). To account for the coding overhead, the packet length increases to $l = 425$ for $t = 1$ correctable bit, and to $l = 433$ bits for $t = 2$ correctable bits. These numbers were obtained from evaluating the Hamming bound [9].
- D is the number of admissible trials before a packet of length l misses its deadline. In case no FEC is used ($t = 0$), we assume $D = 10$, higher numbers need unacceptable simulation runtimes to achieve reasonable statistical accuracy. On the other hand, since FEC makes packets longer, fewer packets can be transmitted within the deadline and we assume $D = 9$ in case of $t = 1$ or $t = 2$.
- 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.
- b is the bit rate. We assume $b = 1$ Mbit/s.

TABLE I
FIXED PARAMETERS FOR ALL EXPERIMENTS (CoV = COEFF. OF VARIATION)

Parameter	**Value**
packet length l for $t = 0/1/2$	416/425/433 bits
bit rate b	1 Mbit/s
deadline D for $t = 0/1/2$	10/9/9 packets
$p_{g,g}$(Gilbert-Elliot)	$1 - 1/65,000$
$p_{b,b}$(Gilbert-Elliot)	$1 - 1/10,000$
CoV bad state holding times (Semi-Markov)	10
CoV good state holding times (Semi-Markov)	20

- ω is the interarrival time of requests at the central station. The requests are assumed to arrive periodically. ω must be larger than the deadline to avoid queueing.

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 [24] and 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, motivated by the results of the measurement study [5] we set the coefficient of variation (CoV) for the bad state holding times to 10, and for the good state to 20. Hence, 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 CoVs below one).

VI. Results

A. 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, motivated by the results from Section IV-C. 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 II. In Fig. 2 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 small enough, so that likely only a few bits within a packet are corrupted. For high values of p ($p \geq 0.05$) FEC is actually counterproductive, since the FEC overhead reduces the number of available trials before the deadline expires. The measurement study [5] distinguishes between bit errors and packet losses. Packet losses can be explained by the receiver not acquiring bit synchronization. In such a case 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 measured bit error rates in the remaining packets were in the range

TABLE II
PARAMETERS FOR EXPERIMENT "EFFICIENCY OF REDUNDANCY APPROACHES"

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

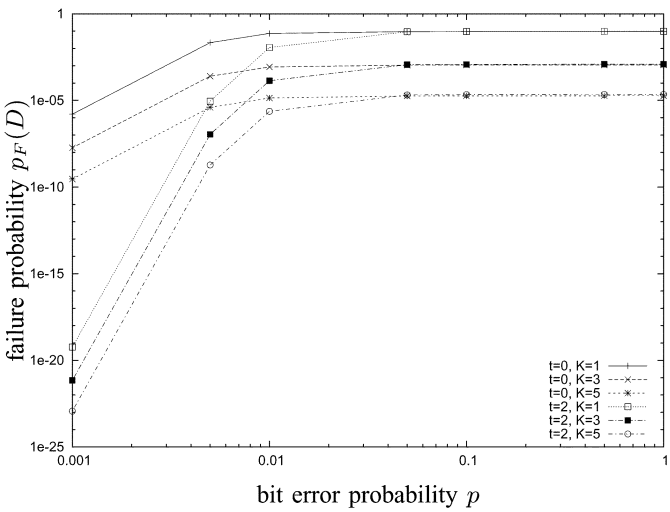

Fig. 2. Failure probabilities versus bit error probability p during bad state for the experiment "Efficiency of Redundancy Approaches", $t \in \{0, 2\}$.

$10^{-2} \ldots 10^{-3}$ at worst, we could recommend that adding antennas is the appropriate measure for combatting packet losses. On the other hand, when the bit error rate p is 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 $p_F(D) \approx 3 \cdot 10^{-10}$, while $t = 2$ and $K = 1$ gives $p_F(D) \approx 5 \cdot 10^{-22}$.

B. 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 ($\omega = 100$ s), which means that the next request hits the respective channels in steady-state conditions. The variable parameters of this experiment are summarized in Table III. 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.

One important result is that for both error models each additional antenna buys approximately one order of magnitude lower failure probability (see Fig. 3). 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-C.

TABLE III
PARAMETERS FOR EXPERIMENT "ANTENNA REDUNDANCY OVER DIFFERENT CHANNELS"

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

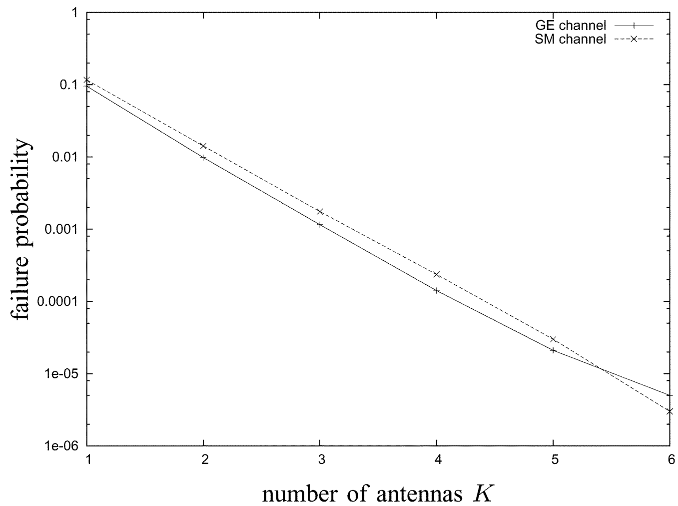

Fig. 3. Failure probabilities for the experiment "effectiveness of antenna redundancy" for two different channel types.

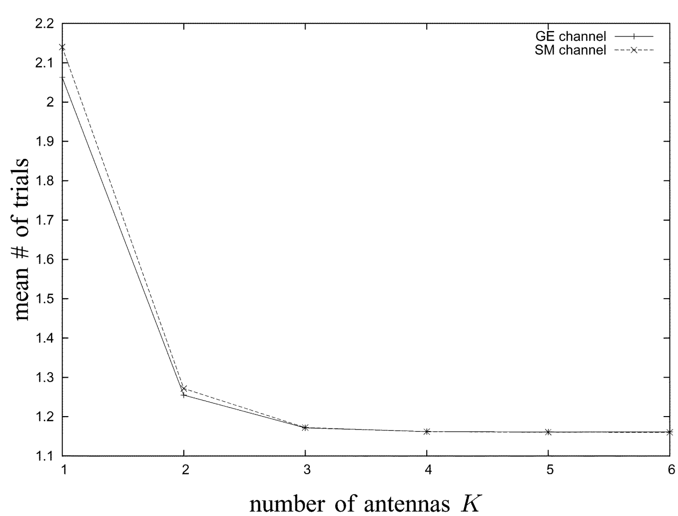

Fig. 4. Mean number of trials for the experiment "Antenna Redundancy over Different Channels".

In Fig. 4, we present the mean number of trials needed to handle a request versus 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.

TABLE IV
PARAMETERS FOR EXPERIMENT "EFFECTIVENESS OF THE ANTENNA REUSE POLICY"

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 ($p = 1$)

C. Experiment: Effectiveness of the Antenna-Reuse Policy

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

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 the antenna where the last successful packet was transmitted is used. The effects of this strategy are evaluated for the two different channel error models. The variable parameters of this experiment are summarized in Table IV.

It is shown in [20] and in Fig. 3 that the Semi-Markov model has consistently higher failure probabilities than the Gilbert–Elliot model. 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 [25, Ch. 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

$$\frac{E[X^2]}{2E[X]} = E[X] \cdot \frac{1 + C_X^2}{2}$$

where C_X^2 is the squared coefficient of variation $C_X^2 = (\mathrm{Var}[X]/(E[X])^2)$. The geometric distributions used in the Gilbert–Elliot model have $C_X < 1$, while for the Semi-Markov model we have used $C_X \in \{10, 20\}$. 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. It is shown in [20] that for the semi-Markov channel much more subsequent requests do fail than for the Gilbert–Elliot model.

In Fig. 5, we show the mean number of packets needed to handle a request until it is successful or reaches its deadline.

- 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, the gain decreases for increasing arrival period, until eventually the antenna reuse strategy gives no gain over the scheme without antenna reuse.

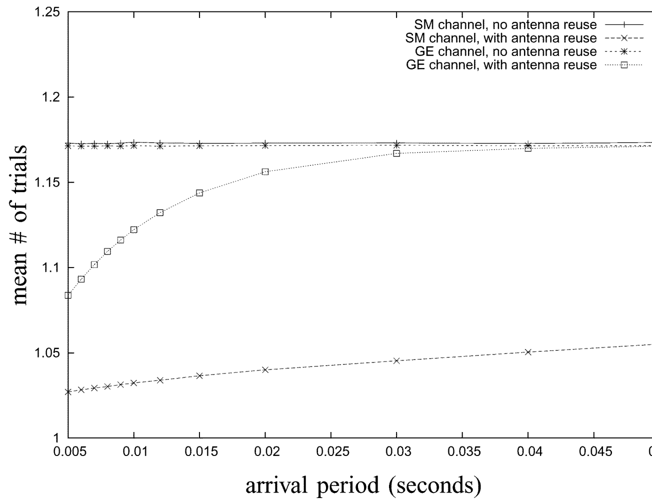

Fig. 5. Mean number of trials for the experiment "effectiveness of antenna reuse policy" for two different channel types.

- 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 the case for the last successful packet of the preceding request), it tends 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 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 redundancy and diversity mechanisms to reduce the failure probability of a basic ARQ protocol. This failure probability, i.e., the probability to miss a prescribed deadline, is of utmost importance for the application of wireless LAN technology in industrial environments. Antenna redundancy explores the advantages of spatial diversity, while keeping the complexity of the receiver low. This makes the implementation of antenna redundancy attractive in scenarios where the wireless stations are small and cheap field devices (for example sensors).

For independent (and rather bad) channels between the antennas and a wireless station, antenna redundancy truly decreases the failure probability, in our example 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). As compared to FEC coding, the antenna redundancy approach is most effective when the error rates are very high, while FEC is more effective when error rates are low enough to distort only a few bits. The multicopy-ARQ approach does not behave well over bursty channels.

To conclude the paper, we discuss possible research directions, both theoretical and practical. First, is very interesting to investigate the antenna redundancy approach and its tradeoffs with FEC under more realistic channel models, including the case of correlated channels, which may occur, for example, when the receiver is placed close to an interferer. 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. 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.

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REFERENCES

[1] J.-D. Decotignie, "Wireless fieldbusses—A survey of issues and solutions," in *Proc. 15th IFAC World Congr. Automatic Control (IFAC 2002)*, Barcelona, Spain, 2002.

[2] A. Willig, "Polling-based MAC protocols for improving realtime performance in a wireless PROFIBUS," *IEEE Trans. Ind. Electron.*, vol. 50, pp. 806–817, Aug. 2003.

[3] L. Rauchhaupt, "System and device architecture of a radio-based fieldbus—The RFieldbus system," in *Proc. Fourth IEEE Workshop on Factory Communication Systems 2002 (WFCS 2002)*, Vasteras, Sweden, 2002.

[4] S. Lee, K. C. Lee, M. H. Lee, and F. Harashima, "Integration of mobile vehicles for automated material handling using PROFIBUS and IEEE 802.11 networks," *IEEE Trans. Ind. Electron.*, vol. 49, no. 3, pp. 693–701, Jun. 2002.

[5] A. Willig, M. Kubisch, C. Hoene, and A. Wolisz, "Measurements of a wireless link in an industrial environment using an IEEE 802.11-compliant physical layer," *IEEE Trans. Ind. Electron.*, vol. 49, pp. 1265–1282, 2002.

[6] D. A. Eckhardt and P. Steenkiste, "A trace-based evaluation of adaptive error correction for a wireless local area network," *MONET—Mobile Networks Applicat.*, vol. 4, pp. 273–287, 1999.

[7] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris, "Link-level measurements from an 802.11b mesh network," in *Proc. of ACM SIGCOMM'2004 Conference*, Portland, OR, Aug. 2004.

[8] H. Liu, H. Ma, M. E. Zarki, and S. Gupta, "Error control schemes for networks: An overview," *MONET—Mobile Networks Applicat.*, vol. 2, no. 2, pp. 167–182, 1997.

[9] S. Lin and D. J. Costello, *Error Control Coding*, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 2004.

[10] A. Annamalai and V. K. Bhargava, "Analysis and optimization of adaptive multicopy transmission ARQ protocols for time-varying channels," *IEEE Trans. Commun.*, vol. 46, pp. 1356–1368, 1998.

[11] T. S. Rappaport, *Wireless Communications—Principles and Practice*. Upper Saddle River, NJ: Prentice-Hall, 2002.

[12] A. Paulraj, "Diversity techniques," in *The Communications Handbook*, J. D. Gibson, Ed. Boca Raton, FL: CRC/IEEE Press, 1996, pp. 213–223.

[13] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[14] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, pp. 1451–1458, Oct. 1998.

[15] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bölcskei, "An overview of MIMO communications—A key to gigabit wireless," *Proc. IEEE*, vol. 92, no. 2, pp. 198–218, Feb. 2004.

[16] E. N. Gilbert, "Capacity of a burst-noise channel," *Bell Syst. Tech. J.*, vol. 39, pp. 1253–1265, Sep. 1960.

[17] E. O. Elliot, "Estimates of error rates for codes on burst-noise channels," *Bell Syst. Tech. J.*, vol. 42, pp. 1977–1997, Sep. 1963.

[18] M. Zorzi, R. R. Rao, and L. B. Milstein, "Error statistics in data transmission over fading channels," *IEEE Trans. Commun.*, vol. 46, no. 11, pp. 1468–1477, Nov. 1998.

[19] A. Willig, "Antenna redundancy for increasing transmission reliability in wireless industrial LANs," in *Proc. 9th IEEE Int. Conf. Emerging Technologies and Factory Automation, ETFA 2003*, Lisbon, Portugal, 2003, pp. 7–14.

[20] ——, "Redundancy Concepts to Increase Transmission Reliability in Wireless Industrial LANs—(Extended Version)," Telecommunication Networks Group, Tech. Univ. Berlin, Germany, TKN Tech. Rep. Series TKN-05-002, 2005.

[21] "Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," LAN/MAN Standards Committee of the IEEE Computer Society, 1999.

[22] *CSIM18 Simulation Engine—Users Guide*, T. B. Lane, Ed., Mesquite Software, Inc, Austin, Texas, 1997.

[23] G. L. Steele, *Common LISP—The Language*, 2nd ed. Amsterdam, The Netherlands: Elsevier/Digital Press, 1990.

[24] A. Willig and A. Wolisz, "Ring stability of the PROFIBUS token passing protocol over error prone links," *IEEE Trans. Ind. Electron.*, vol. 48, no. 5, pp. 1025–1033, Oct. 2001.

[25] S. M. Ross, *Applied Probability Models With Optimization Applications*. New York: Dover, 1992.

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