Industrial Wireless Networks

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The Significance of Timeliness in Communication Systems

In the last few years, wireless networks have gained significant importance in the context of industrial communication systems [1], where their deployment is bringing several noticeable benefits, ranging from replacement of cables to the connection of devices that cannot be reached by traditional wired systems. These features make the adoption of wireless networks for industrial applications very attractive, and they are envisaged to be deployed even more in the future, either as stand-alone systems or arranged in hybrid (wired/wireless) configurations. Unfortunately, wireless communication systems are often characterized by well-known problems, such as fading, multipath propagation, shadowing, and interference, that have the undesired effect of increasing the bit error rate (BER), resulting in the introduction of delays as well as randomness in packet delivery. Moreover, in the context of industrial communication, these aspects may be exacerbated by the specific nature of the environment. Indeed, the rapid movement of machineries along with the possible presence of electromagnetic interference sources, which are typical of manufacturing sites, may introduce considerable fluctuations of the BER values that contribute to further degradation in communication quality.

All of these phenomena may have a negative impact on the performance of industrial wireless communication systems, particularly on their timeliness. This is a crucial aspect, since such systems are often required to provide very tight timing performance as dictated by

Digital Object Identifier 10.1109/MIE.2013.2253837
Date of publication: 17 June 2013

1932-4529/13/$31.00©2013IEEE

the typical application fields in which they are employed, such as factory automation, process control, and manufacturing systems [2]–[4].

Timeliness, in a literal sense, is a general term that indicates the ability to cope with some timing constraints. As such, it has been adopted in the industrial communication scenario. In this context, an actual timeliness assessment can be performed through the evaluation of some performance indicators that are tailored to the specific network employments.

In particular, several applications require that some process data are periodically delivered at precise instants (such as, for example, in motion control systems). In this type of application, when communication networks are employed [5], suitable performance indicators to evaluate their timeliness are represented by both the cycle time values that can be achieved by the networks and the maximum jitter that may affect the execution of cyclic operations [6].

On the other hand, for different kinds of applications, like those concerned with event-driven systems such as remote monitoring, timeliness may be better addressed referring to the maximum delivery time of acyclic data, since this metric allows for estimation of the capability of the network to promptly notify the occurrence of critical, unpredictable events, such as alarms.

The analysis we provide is mainly focused on both the physical and the data link layers, since industrial networks are typically based on reduced protocol stacks that, as such, strongly rely on these layers to provide adequate timeliness. Moreover, high-layer protocols adopted by different industrial wireless networks, although not interoperable, frequently rely (at least partially) on common, standardized, low-level protocols [7].

An example in this direction is given by the well-known standards used for process control and building automation, such as wireless highway addressable remote transducer (HART) [8], ISA 100.11a [9], and ZigBee [10], which rely on the IEEE 802.15.4 Wireless Personal Area Network (WPAN) [11]. Similarly, IPv6 over low-power wireless personal area networks (6LoWPAN) [12], a standard that is beginning to be employed even in the industrial environment, defines an adaptation layer that allows the use of IPv6 communication services on top of IEEE 802.15.4.

Further examples of this type are the applications described in [13], in which the authors report the deployment of an IEEE 802.15.4–based sensor network in an oil refinery, and [14], where the authors discuss the adoption of industrial wireless sensor networks (IWSNs) for intrusion detection systems. Finally, it is worth mentioning the popular wireless interface for sensors and actuators (WISA) [15], [16], which implements a master–slave protocol exploiting the physical layer of the IEEE 802.15.1 WPAN (Bluetooth) [17].

Timeliness Issues of Industrial Wireless Networks

The protocols adopted by industrial networks typically use error detection and control techniques that are analogous to those of general-purpose communication systems. Among these techniques, the most popularly employed in case of packet loss, particularly at the data link layer level, is represented by the automatic repeat request (ARQ).

In practice, a frame that undergoes a transmission error is retransmitted, either when a negative acknowledgment is received by the source station or after the occurrence of a time-out in receiving the expected acknowledgment frame. Usually, an adequate number of retransmission attempts are granted to a transmitting station in order to limit the percentage of lost frames to very low values.

While this strategy increases reliability (roughly, the more the transmission attempts, the higher the final success probability), it may be dangerous for the timeliness of industrial communication systems (and for the performance of the applications that employ them), since it introduces some uncertainty in packet delivery, possibly causing jitter on the periodic operations as well as missing of event notification deadlines.

To this regard, let us consider, for example, a master–slave network based on a pure round robin polling strategy comprising one master and ten slave devices, and suppose that the polling time is the same for each slave. If (due to some error), during a cycle, a slave requires three transmission attempts in order to be successfully polled, then that cycle will take 20% more time than the previous ones without taking into account the possible introduction of waiting times between a transmission attempt and the following one.

This problem may become particularly critical for industrial wireless networks, since the higher BERs could cause frequent failures. Consequently, several transmission attempts may be required in order to successfully deliver a packet.

Furthermore, several protocols (mostly those based on random access techniques) introduce progressively increasing backoff times that have to elapse between one transmission attempt and the next. The values assumed by the backoff times may be significant, as can be seen, for example, in Figure 1, which reports these times

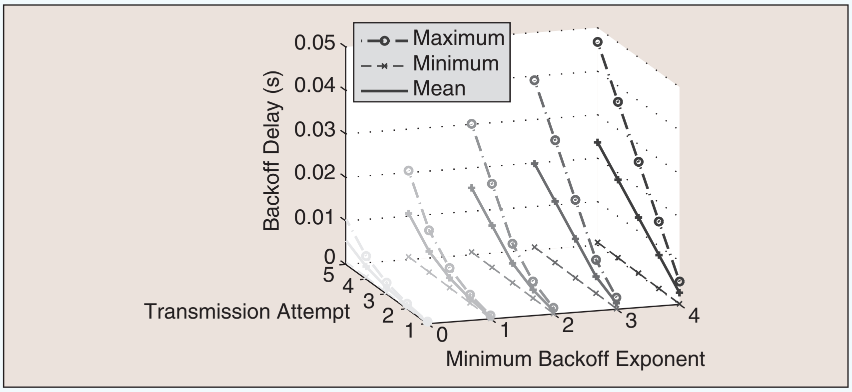


FIGURE 1 – Backoff time for IEEE 802.15.4 networks (values derived directly from the standard).

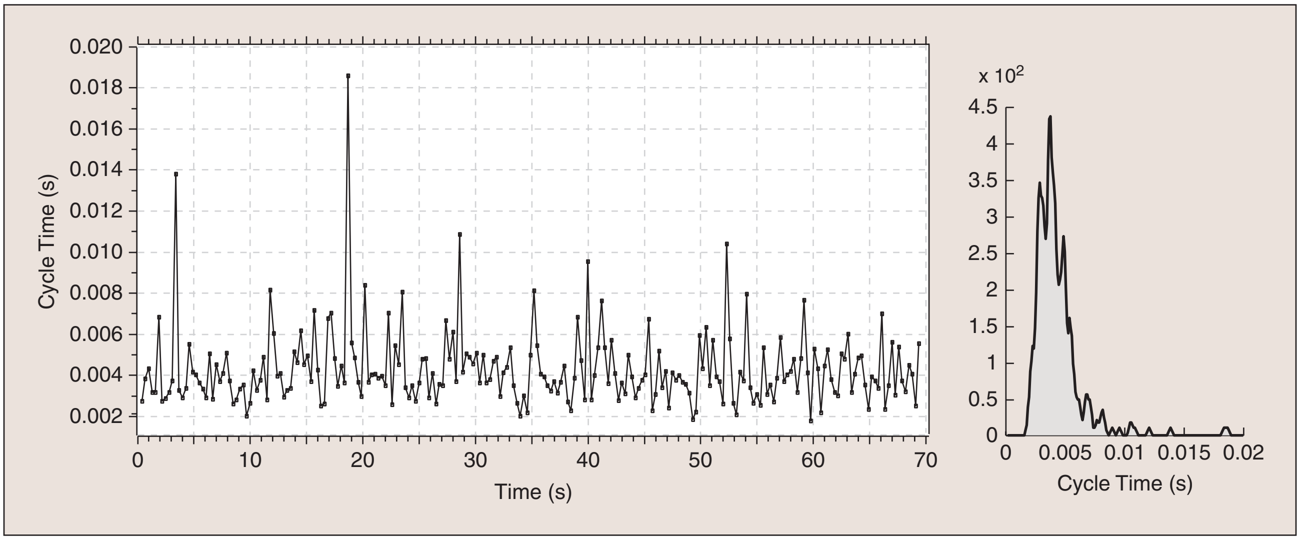


FIGURE 2 – Behavior of cycle time and PDF for a master–slave application based on IEEE 802.11.

for the IEEE 802.15.4 WPAN versus the number of transmission attempts, as derived directly from the standard. In the figure, it is worth observing that the backoff time, besides depending on the number of transmission attempts, is strongly related to the minimum backoff exponent medium access control (MAC) parameter (an integer used by the algorithm that calculates the actual value of the backoff time, referred to as macMinBE in the standard) whose default value is three.

From the preceding examples, the ultimate undesired effect of the retransmissions is evident. Indeed, the service time (i.e., the time necessary to deliver a packet) reveals to be a random variable that, as such, negatively reflects on several other important performance indicators of industrial wireless networks [18], [19].

To this regard, let us go back to the case of the master–slave network and suppose that it is implemented by a popular IEEE 802.11 g WLAN, working at 54 Mb/s, with each slave exchanging 10 I/O bytes with the master. We consider, as a meaningful performance indicator, the cycle time of the network [20], i.e., the time employed by the master to execute a complete polling sequence on the slaves (which is clearly dependent on the service time). From a theoretical analysis based on the structure of the frames exchanged, the polling of a slave (which implies the transmission of both a request and a response frame, including their acknowledgments) would require 168 μs, leading to a *constant* theoretical cycle time of 1.68 ms. It is worth remembering that the access to the communication medium is ruled by the master and, hence, nodes do not have to compete for gaining network access.

Conversely, Figure 2, which shows both the cycle time behavior and its probability density function (PDF), reveals an evident randomness due to the occurrence of both packet retransmissions and backoff procedures. Results have been obtained via numerical simulations carried out with OMNeT++ [21], using the default MAC parameters and assuming a constant, nonideal signal-to-noise ratio (SNR).

Retransmissions, however, often cannot be avoided. Nevertheless, strategies to mitigate their negative effects can be undertaken. Particularly, an adequate tuning of the MAC parameters is a possible solution. For example, reduction of the backoff time would have the immediate benefit of significantly limiting the randomness of the cycle time. This is confirmed by some additional simulations we carried out, in which the backoff time was progressively reduced. Table 1 reports the statistics of the cycle time obtained from these tests. Specifically, Table 1 refers to the following three cases: default backoff (Def_BO) (simulation carried out using the default MAC parameters, as derived from the standard), 50%_BO (backoff time reduced by 50% on average with respect to the default value), and Zero_BO (backoff time set to zero). As expected, the statistics of the cycle time significantly improved when the backoff time was reduced.

Unfortunately, commercial IEEE 802.11 devices often allow only limited access to the MAC parameters; thus, the tuning cannot be completely exploited. Conversely, a better situation may be encountered for some IEEE 802.15.4-based devices such as motes, which are typically deployed in IWSNs, since for such devices the protocol stacks are usually implemented and released in source code, granting,

TABLE 1—STATISTICS OF THE CYCLE TIME FOR THE IEEE 802.11 EXAMPLE WITH DIFFERENT BACKOFF TIMES.

METRIC	DEF_BO	50%_BO	ZERO_BO
Mean (ms)	4.29	3.40	2.52
Variance (ms^2)	3.80	1.36	0.12
Minimum (ms)	1.81	1.81	1.79
Maximum (ms)	18.62	11.42	3.91

in this way, access to the whole set of parameters.

Timeliness Enhancements

As a general measure, the timeliness of a communication system may be enhanced by the use of protocols that ensure an ordered access to the transmission medium. This feature has been adopted by most of the available industrial wireless networks, since it reveals to be particularly beneficial. Indeed, it allows channel access contentions (and the consequent possibility of wasted backoff times) to be avoided, as well as significant reduction of frame collisions.

Among the various strategies that grant an ordered access, one of the most popular relies on time-division multiple access (TDMA). With such a technique, stations are assigned predefined time slots, during which they have exclusive access to the network. A further commonly available opportunity to enhance timeliness is represented by frame prioritization. In this case, trivially, greater priorities are assigned to urgent frames in order to ensure their timely delivery.

In the following text, we address some more specific techniques that may lead to improved timeliness of industrial wireless networks, as derived from both the scientific literature and common working practice.

Improved Retransmission Strategies

The characteristics of the industrial wireless communication channel have been deeply investigated in the last few years [22], [23]. As a general result of these analyses, the channel showed an alternation of good and bad states over time. This behavior can be approximated by a Gilbert–Elliot [24] model that, although rather simplified, ensures good analytical tractability. As a matter of fact, with such channel behavior, the traditional retransmission strategy described in the section "Timeliness Issues of Industrial Wireless Networks" (immediate repetition of a transmission in case of failure, possibly after a random backoff time has elapsed) reveals to be even more ineffective.

Generally speaking, since errors occur as bursts, there is a nonnegligible probability that a new immediate transmission toward the same node will take place while the error burst that affected the communication link between the two addressed nodes has not yet ended. In other words, there is the concrete risk that the new transmission will be undertaken while the link between the two nodes is still in a bad state, resulting in a new failure.

This problem is addressed in [25], in which the authors propose some improved retransmission strategies that actually provide better performance than the traditional strategy. Particularly, among the others, an adaptive scheme is taken into consideration for a master–slave network, in which the polling sequence executed by the master on the slaves is established on the basis of a statistic of the success probability in polling each slave. In practice, if some slaves have to be polled consecutively by a controller, then the sequence of queries starts with the device that, in the past, showed the highest poll success probability. It is worth observing, however, that this strategy, although beneficial, may introduce a dynamic change of the polling order that, as such, could not always be feasible. This is the case, for example, in applications in which one or more slaves have to be mandatorily polled at the beginning of a cycle, since their data have to be made available to the other slaves in the same cycle.

The practical implementation of the proposed retransmission strategies requires modification of the MAC protocol. As outlined in the section "Timeliness Issues of Industrial Wireless Networks," such a possibility is commonly granted, for example, by some kinds of IEEE 802.15.4 devices (i.e., motes) for which the implementation can be made via adequate programming of low-level protocol primitives (as actually done by the authors of [25]). Conversely, devices based on different wireless technologies (e.g., IEEE 802.11) usually do not provide access to the MAC protocol. Consequently, in such cases, the necessary modifications should be carried out by the manufacturers acting directly on the firmware of the devices.

Improved retransmission strategies are expected to introduce relevant benefits in terms of both timeliness and reliability. Indeed, the results shown in [25] clearly indicate that adaptive schemes allow a better (lower) difference between maximum and minimum slave response times to be obtained, reducing the randomness of the polling operations. Moreover, with such schemes, the average number of unserved slaves (which reflects the polling failures) is kept at very low values.

As a final consideration about low-level retransmission strategies, it is worth observing that they have a strong impact on the high-level real-time applications that may rely on them. For example, as outlined in both [26] and [27], the admission control test for a wireless network equipped with a real-time message scheduler has to take into consideration the occurrence of transmission errors as well as the specific strategy adopted by network protocols to handle them. Particularly, the knowledge of the time requested by the low-level retransmissions is key information that allows the scheduling algorithm to reserve in advance the adequate bandwidth to avoid the problem of missing deadlines.

Rate Adaptation

This technique, in principle, can be adopted by any wireless network able to dynamically change its transmission rate, since it is based on the possibility of modifying the transmission rate in agreement with the channel state fluctuations. The basic idea relies on the fact that the modulation techniques employed at the lower rates are less affected by noise. Thus, reducing the transmission rate is an effective technique to ensure packet delivery even in the presence of low SNRs.

To select the most suitable rate, an estimate of the SNR of the channel would be necessary but, unfortunately, this is not commonly achievable with the available radio components. As a possible solution, the SNR could be roughly evaluated from the received signal strength indicator, a metric that can be obtained by a preliminary message exchange among stations wishing to communicate, which has to take place before the beginning of the actual data transfer. However, this solution introduces a relevant transmission overhead that heavily impacts the overall efficiency of industrial communication systems, as they typically employ limited payloads. Consequently, some different rate adaptation techniques have been conceived that provide an indirect estimate of the SNR.

The most popular technique of this type, which has been proposed for WLANs, is known as automatic rate fallback (ARF) [28], [29]. In practice, ARF compels a station to reduce its transmission rate (to the immediately lower rate in the available set) after K consecutive failed attempts to transmit a frame, whereas that station increases the rate to the next upper value after N successful attempts. Usually we have $K = 2,\ N = 10$. Unfortunately, ARF is often not suitable for industrial networks, since it may negatively impact their timeliness.

For example, let us consider an IEEE 802.11 application (ARF is actually adopted by most of IEEE 802.11 devices) and suppose, for example, that a burst of noise suddenly occurs on the channel that diminishes the SNR in such a way that the transmission rate of a station that is delivering a frame has to be reduced from 54 Mb/s to 24 Mb/s to achieve a good transmission probability. In this case, ARF would likely undergo seven transmission attempts to correctly deliver the frame (two failures per each transmission rate in the set between 54 and 24 Mb/s), leading to a highly random and possibly intolerable service time value.

An obvious, immediate solution to this problem consists in setting the transmission rate to a low value. However, this choice may reveal to be not optimal in terms of service times, particularly in the presence of variable SNRs as it often happens in industrial environments. To this regard, let us go back to the transmission of an IEEE 802.11 frame from a station to another and suppose it carries 10 bytes of useful data. The minimum service time (calculated when the sending station has immediate, successful, access to the network) of such a frame is, respectively, 182 μs at 6 Mb/s and 106 μs at 54 Mb/s. Clearly, these values may lead to significant performance differences even for configurations comprising a limited number of nodes (e.g., the same operation repeated consecutively on five nodes would require 1820 μs in one case and 1,060 μs in the other one). Moreover, an increase in the payload, as could be requested, for example, by multimedia industrial applications [30], would make the difference even more relevant. As a consequence, the choice of the transmission rate represents a critical aspect of timeliness that needs to be adequately investigated. Such an issue has been addressed in [31], where we proposed two alternative rate adaptation techniques, namely static retransmission rate ARF (SARF) and fast rate reduction ARF (FARF), specifically conceived for real-time industrial applications. In practice, SARF has a behavior similar to that of ARF but it specifies each retransmission attempt to take place at the lowest rate specified by IEEE 802.11g (6 Mb/s), ensuring that the most robust modulation is used. However, the FARF technique is a version of ARF in which every failure forces 6 Mb/s as the new transmission rate. Subsequently, the increase in the rate follows the ARF common behavior. Both these techniques dramatically reduce the number of transmission attempts, and hence improve timeliness, since every retransmission of a packet is carried out at the lowest rate. To this regard, in the aforementioned example, both the techniques would go through only one failed transmission attempt before correctly delivering the frame (at 6 Mb/s).

Analogously to the case discussed in the previous subsection, the practical implementation of the proposed techniques, although simple, requires access to the MAC protocol. Consequently, such an implementation either can only take place on devices that support this feature or requires a modification of the device's firmware.

Frequency Diversity

Frequency diversity is a strategy that allows increased immunity against interference arising from other communication systems, a well-known problem that affects industrial wireless networks, causing frequent retransmissions due to frame collisions with the consequent negative impact on timeliness.

Industrial wireless communication systems are usually allocated in the industrial scientific medical (ISM) band at 2.4 GHz. Unfortunately, in this band, several different communication systems may operate, increasing the risk of mutual interference. To this regard, the IEEE has published a recommended practice intended to ensure coexistence between communication systems working in unlicensed bands [32]. Moreover, this problem has been extensively addressed by the scientific community, as can be seen, for example, in [33], [34]. Also, a particular case of interference is represented by so-called cross-channel interference, a phenomenon that might affect transmissions belonging to the same communication system allocated on different (adjacent) radio channels, as addressed in [35] for IEEE 802.15.4/ZigBee networks.

The most popular technique adopted to achieve frequency diversity is represented by frequency hopping. This consists, in practice, of a rapid switching of the transmitting carrier among several frequency channels (sometimes referred to as hopsets) according to a pseudorandom sequence. An improvement on this technique, adaptive frequency hopping [36], basically allows a network to exclude from the hopsets frequencies that could interfere with those employed by neighboring networks, either statically or dynamically.

It is worth mentioning that frequency hopping has been adopted at the physical layer of some industrial wireless networks, such as Wireless HART and ISA 10.11a. Moreover, in the context of WPANs, frequency hopping is employed by the physical layer of IEEE 802.15.1.

Frequency hopping (either adaptive or not) has a positive impact on the timeliness of industrial wireless networks, since, intuitively, it ensures good immunity toward communication systems that transmit on fixed frequency channels. To this regard, some interesting results are presented in [37], [38]. However, dynamically changing the transmission frequencies of a device requires in-depth modifications to its hardware configuration. For this reason, frequency hopping cannot be thought of as an option for devices that do not natively support it.

Spatial Diversity

Spatial diversity techniques are based on the contemporaneous use of different, and possibly independent, transmission paths between two stations. In this way, the probability that a transmission will be successful in the first attempt is increased with consequent improvement of the timeliness. Spatial diversity may be achieved in two ways, represented by multiple-input, multiple-output (MIMO) systems [39] and cooperative networks [40], respectively.

In MIMO systems, both transmitter and receiver devices may be equipped with more than one antenna, as can be seen in Figure 3, which shows a simple two-station example. MIMO systems, in general, can be classified into three categories, namely, precoding, spatial multiplexing, and diversity coding. With precoding, the same signal is transmitted by more antennas to improve the robustness of the link between transmitter and receiver. To obtain the best performance, it is necessary to adequately treat the signal to be sent. This is usually done with a technique called beamforming, which involves assigning different weights to the signal transmitted by the different antennas in agreement with some channel state information that must be known in advance at the transmitter.

With spatial multiplexing, the different antennas may transmit different signals on different paths. This is an effective technique to increase the overall channel capacity in that, if an adequate spatial diversity among the different transmitted streams is maintained, then those streams may be received simultaneously. In diversity coding, the same signal is transmitted, but in this case, there is no knowledge of the channel state, so beamforming cannot be applied. Multiple antennas are used on the receiver side, requiring an adequate selection on the several received streams (which actually could also be due to multipath) in order to extract the received signal. Some different combining techniques can be applied in this case, as outlined in [39].

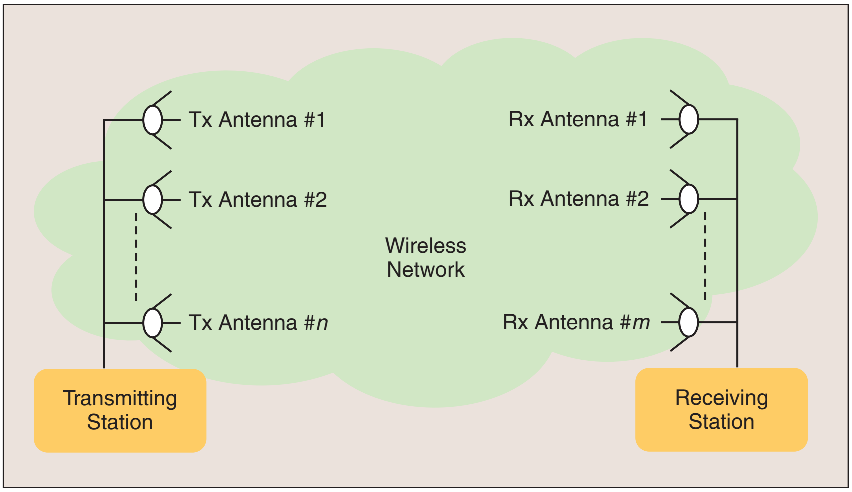


FIGURE 3 – Example of a MIMO system.

To enhance the timeliness of MIMO-based industrial wireless communication systems, both precoding and diversity coding techniques represent very attractive solutions, since they increase substantially the probability that a frame will be correctly received on the first transmission attempt. However, since channel state information is usually not known at the transmitter, beamforming cannot be effectively carried out. As a consequence, diversity coding seems to be the most suitable technique.

In cooperative networks, a transmission between two stations is achieved with the help of some further nodes called relayers [41], which actually cooperate to forward data to the destination via multiple paths. These nodes may or may not be equipped with multiple antennas. In any case, regardless of the configuration of the cooperating nodes, they need to be coordinated, and this is an aspect that increases the complexity of this spatial diversity technique.

Summary of Timeliness Enhancement Techniques

Table 2 summarizes the timeliness enhancement techniques outlined in this section along with some information about their practical implementation aspects. Particularly, for each of the mentioned techniques, the table specifies at which layer of the protocol stack it is required to access in order to practically implement the technique. Moreover, in a further column we consider the most popular WLANs/WPANs standards, referring specifically to IEEE 802.11, IEEE 802.15.4, and IEEE 802.15.1 (since they are the communication systems on which most of the industrial wireless networks rely) and we indicate which of them natively implement the mentioned timeliness enhancement techniques.

TABLE 2—SUMMARY OF TIMELINESS ENHANCEMENT TECHNIQUES.

TECHNIQUE	ACCESS	IMPLEMENTED BY
Ordered access	MAC	802.11, 802.15.4, 802.15.1
Frame prioritization	MAC	802.11
Improved retransmissions	MAC	–
Rate adaptation	MAC	802.11
Frequency diversity	PHY	802.15.1
Spatial diversity	PHY/MAC	802.11

Timeliness of Available Industrial Wireless Networks

In this section, we analyze how timeliness issues are addressed by some of the most popular industrial wireless networks.

Wireless HART and ISA 100.11a

Both Wireless HART and ISA 100.11a are the two leading standards in the context of IWSNs. Basically, they allow for a connection of a relevant number of (field) devices, implementing various configurations, with the great advantage of avoiding (wired) cable connections. These features make them particularly suitable for applications such as process automation/control, even for plants distributed over extended geographical areas. Although there are some significant differences between Wireless HART and ISA 100.11a, both networks define similar devices that are concerned with the typical applications for which the networks are conceived.

The protocol stacks of both Wireless HART and ISA 100.11a are quite similar, as described in [42]. At the lowest layer, these networks make use of the physical transmission system defined by IEEE 802.15.4, with a rate of 250 Kb/s in the 2.4 GHz ISM unlicensed band. The data link layers are slightly different; nonetheless, both networks are based on a slotted transmission, which specifies that each transaction on the network has to take place within a slot whose duration is set to 10 ms in Wireless HART, whereas ISA 100.11a supports different values. Slots can be either dedicated or shared, meaning that access to the network by the stations may be either ordered (as in the case of dedicated slots) or random (shared slots). Particularly, in this latter case, stations that want to transmit on a slot use a carrier sense multiple access with collision avoidance (CSMA/CA) technique to compete for channel access. Data transmission on the network is achieved via superframes that represent groups of slots. The data rate of both Wireless HART and ISA 100.11a, along with the characteristics of their MAC layer protocols (particularly the structure of the superframes), suggests that they are suitable for applications that require both cycle times and maximum delivery times of the acyclic data ranging from hundreds of milliseconds to a few seconds.

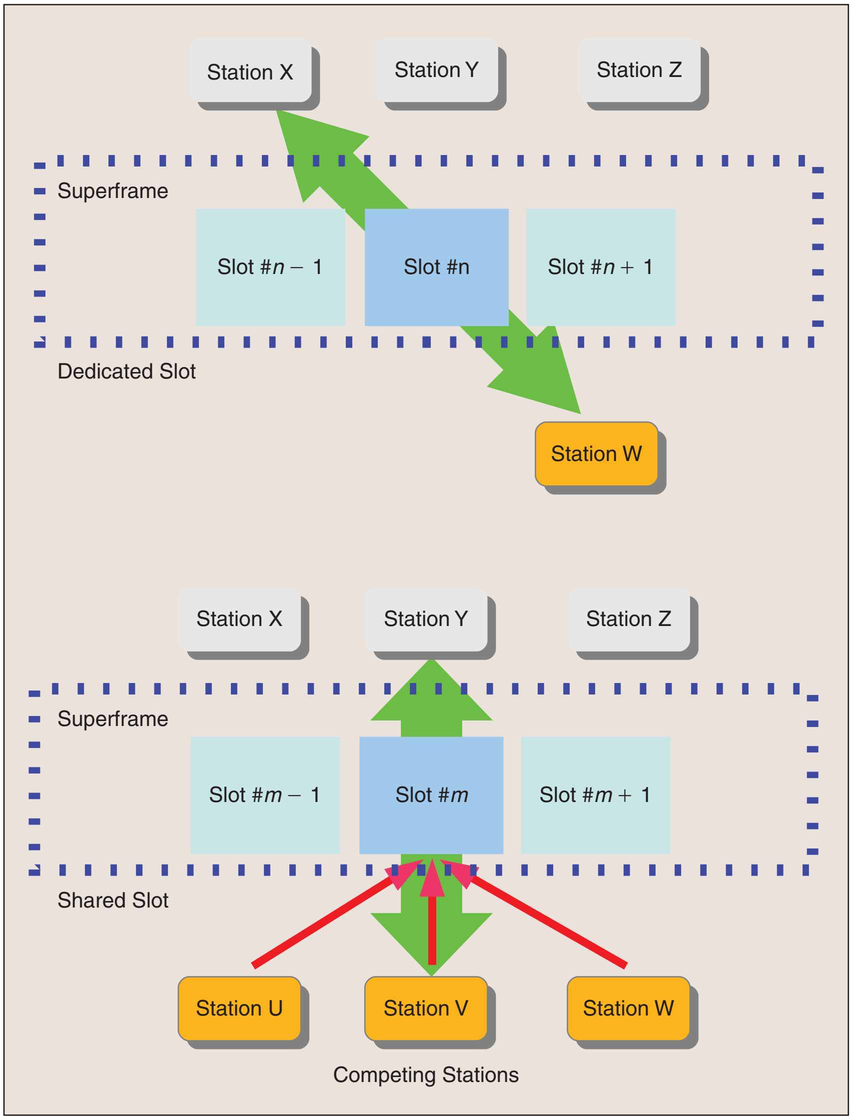


FIGURE 4 – Example of slotted communication.

Figure 4 shows an example of a data transmission. The upper side refers to the dedicated slot *n*, where the communication between station *W* and station *X* takes place immediately, since station *W* is supposed to have reserved access to the slot. Conversely, in the lower side of Figure 4, where slot *m* is shared, three stations (*U*, *V*, and *W*) are assumed to compete for access to the slot. In the example, it is supposed that station *V* will win the competition and, consequently, start a communication with station *Y*.

The strategy adopted by the data link layers of both Wireless HART and ISA 10.11a to ensure adequate timeliness is represented by the combination of a TDMA technique, used to access the physical medium, with pseudorandom frequency hopping. The TDMA technique is implemented via the set of dedicated slots that grant devices exclusive access (i.e., without contention) to the network, avoiding any further waiting time. Moreover, retransmissions in case of failures take place in the next available slot without introducing any further randomness. On the other hand, frequency hopping is achieved by randomly changing the transmission channel used by any given slot. In practice, moving from one slot to the next implies the change of transmission channel according to a random sequence. Such a technique clearly ensures good immunity to narrow band interference. Furthermore, the combination of TDMA and frequency hopping allows for the accommodation of more than one transaction on a single slot, with the consequent increase in the system throughput.

Both Wireless HART and ISA 100.11a have an additional interesting feature that allows them to increase both timeliness and reliability through the implementation of spatial diversity. In practice, for a given network configuration, a link between any two devices may be achieved via several different physical paths. The whole set of these paths, known as a graph, is preconfigured offline and identified by a graph ID. Thus, a message originating from a station may reach its final destination through different paths. Stations on the route are responsible for the choice of the path on which the message has to be forwarded within a specified graph. Such a choice is carried out on the basis of a graph table that is maintained on each station.

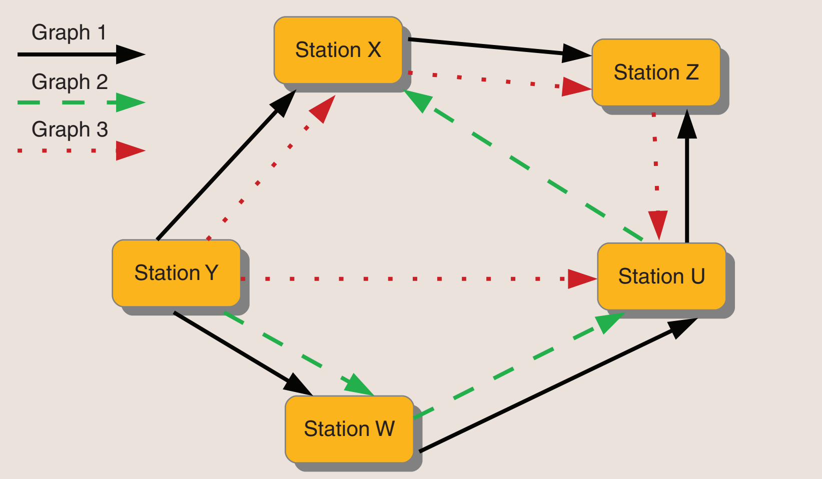
Figure 5 provides an example of graph routing for a network that comprises five stations that are crossed by three different graphs. Here, a message originating from station Y and directed to station U may be routed on all of the three different graphs shown in the figure. If, for example, graph 3 is chosen, then the sending station has to select one of the two possible paths (either $Y \rightarrow U$ or $Y \rightarrow X \rightarrow Z \rightarrow U$) to forward the message. The choice may be arbitrary or not, given that one of the two possibilities might be specified as preferred, in which case, that the first transmission will have to take place on the preferred link. If the transmission is not successful (i.e., an acknowledgment is not received by the sending station), then a new transmission attempt will be made on the alternative path, implementing, in this way, spatial diversity. Conversely, if in Figure 5, either graph 1 or graph 2 was chosen, then spatial diversity could not be achieved, since for both the graphs there is only one path from station Y to station U.

Also, Wireless HART supports a further routing technique called superframe routing. In this case, if a station receives a message in which the specified graph ID does not match any of the IDs for which it has been configured, then that station will wait to receive a superframe whose ID is equal to the graph ID specified in the incoming message. In this case, the station will forward the message to all of its neighbors that are addressed in the superframe.

IEEE 802.11–Based Systems

Although there are no standardized industrial communication systems based on the IEEE 802.11 WLAN, such a network has been extensively addressed by the scientific literature since, thanks to its relevant features, it represents an attractive solution for industrial wireless communications. Indeed, the available data rates allow it, at least in principle, to achieve performance figures in the same order of magnitude as those provided by traditional (wired) industrial networks.

There are several practical applications in which IEEE 802.11 has already been deployed, such as the one described in [43]. The use of infrastructure IEEE 802.11 networks is envisaged, in particular, for hybrid systems (wired/wireless), as it represents the natural wireless extension of real-time Ethernet (RTE) networks [44]. In this context, a variant of the IEEE 802.11 MAC protocol has been defined in the EU project Flexware [45] in order to implement a hybrid architecture capable of providing real-time performance [46]. On the other hand, (industrial) ad hoc IEEE 802.11 configurations can be deployed as well, since they are explicitly encompassed by the standard. As a further example, multimedia industrial applications often require adequate quality of service in the presence of relevant



Graph Table Station Y

Graph ID	Neighbor Address
Graph 1	Station X, W
Graph 2	Station W
Graph 3	Station X, U

Graph Table Station X

Graph ID	Neighbor Address
Graph 1	Station Z
Graph 2	/
Graph 3	Station Z

Graph Table Station Z

Graph ID	Neighbor Address
Graph 1	/
Graph 2	/
Graph 3	Station U

Graph Table Station U

Graph ID	Neighbor Address
Graph 1	Station Z
Graph 2	Station X
Graph 3	/

Graph Table Station W

Graph ID	Neighbor Address
Graph 1	Station U
Graph 2	Station U
Graph 3	/

FIGURE 5 – Example of spatial diversity achieved via graph routing.

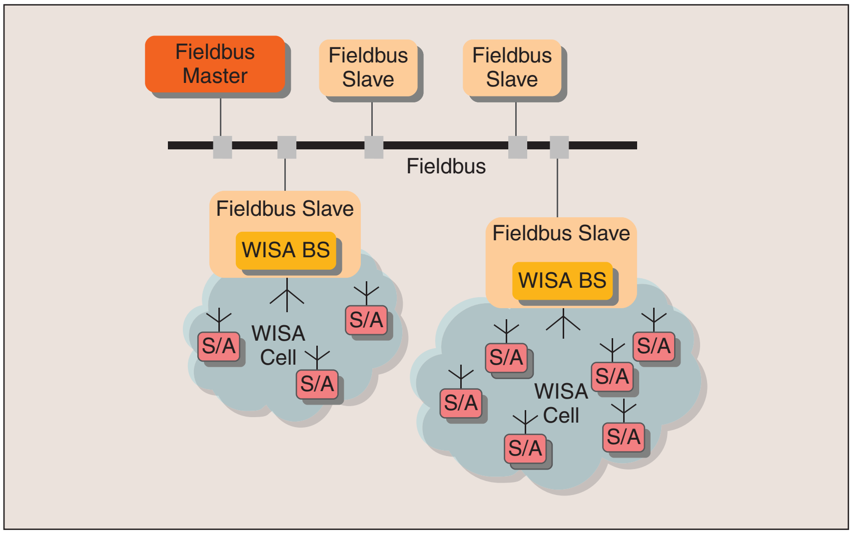


FIGURE 6 – Example of a network using WISA cells.

amounts of data to transfer [47]. In these applications, when a wireless connection is necessary, IEEE 802.11 surely represents the most suitable opportunity, particularly in light of the increased bandwidth made available by IEEE 802.11n.

The timeliness of IEEE 802.11-based systems for industrial applications may be improved in different ways. A first possibility is the introduction of the enhancements to the original MAC layer, provided by IEEE 802.11e. Particularly, as described in [48], the adoption of a mixed scheme that combines the enhanced distributed channel access with a TDMA technique has the beneficial effect of reducing end-to-end delays as well as the number of lost frames. Secondly, as addressed in the section "Rate Adaptation," the careful choice of the transmission rate is a key opportunity that deserves to be profitably exploited.

Finally, it is worth mentioning that spatial diversity is explicitly foreseen by IEEE 802.11. Specifically, MIMO systems can be implemented by both IEEE 802.11g and IEEE 802.11n. As a matter of fact, several devices currently available on the market are equipped with two antennas, for example the access points family specifically conceived for industrial applications described in [49]. Nonetheless, while IEEE 802.11g can only provide both precoding and diversity coding, since it is not able to contemporaneously send different streams on more antennas, IEEE 802.11n allows the complete set of MIMO functionalities, including spatial multiplexing, to be achieved.

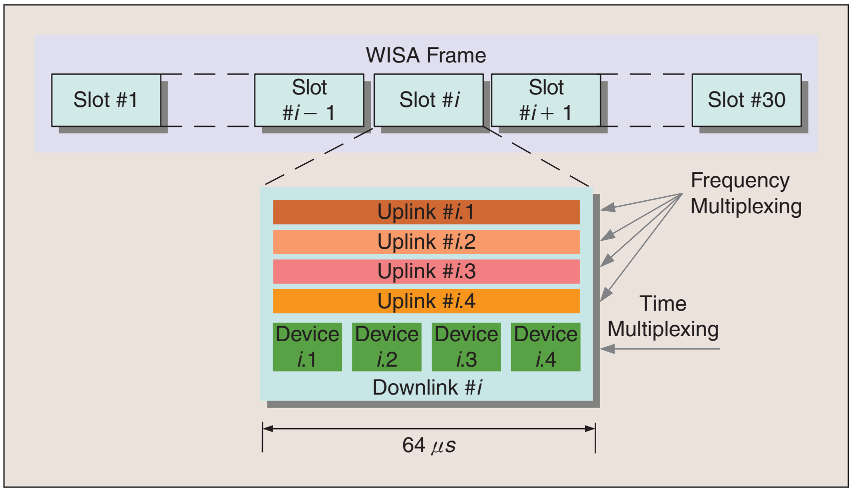


FIGURE 7 – WISA frame showing the structure of Slot #*i*.

WISA

The WISA is a communication system purposely developed to achieve fast and reliable data exchange over a wireless medium at the lowest levels of factory automation systems between a master station, referred to as WISA base station (BS), and up to 120 input slaves or 60 I/O arranged in a wireless cell. The transmission rate is 1 Mbit/s. Such a rate, given the structure of the frames used, ensures the achievement of cycle time values as low as 2 ms and maximum delivery times of acyclic data below 15 ms [16]. Several WISA cells may be connected to a wired network (typically either a fieldbus or an RTE network) via their base stations, implementing configurations such as those shown in Figure 6, where two cells are connected to a wired fieldbus. The features of WISA make it particularly suitable to realize wireless extensions of wired field networks, as described in [50], where the possible adoption of WISA cells to extend Profibus and Profinet networks is proposed.

To guarantee satisfactory timeliness, WISA makes use, at the MAC layer, of frequency hopping associated with a TDMA technique that ensures elimination of channel conflicts. The data exchange between the BS and sensors/actuators takes place within the so-called WISA frame that lasts 2,048 μs and contains 30 slots of duration 64 μs. As shown in Figure 7, which reports the structure of a WISA frame, each slot comprises four uplinks (from sensors to BS), used to transmit data as well as acknowledgments, and one downlink (from BS to actuators). A communication error occurs when a sensor/actuator does not receive the acknowledgment relevant to the transmitted data. In these cases, data are retransmitted in the following frame. All the links use different frequencies so that they are contemporaneously active. Moreover, the five frequencies are changed every time a new WISA frame is issued implementing the frequency hopping technique. It is worth observing that, while the uplinks are based on frequency multiplexing, the downlink uses time multiplexing, since, within a slot, four actuators are addressed in sequence by the BS.

Finally, both timeliness and reliability of WISA networks may be increased with spatial diversity, implemented by means of MIMO systems. However, while in principle, every WISA device may be equipped with multiple antennas, in practice, the deployment of adequately spaced antennas may take place only for base stations.

Summary

Table 3 shows a summary that illustrates whether the timeliness enhancement techniques mentioned in the section "Timeliness Enhancements" are implemented by the commercially available industrial wireless networks. It is worth observing that the technique called improved retransmissions has been marked as implemented for Wireless HART, ISA 100.11a, and WISA, since, although not adaptive, the (different) techniques adopted by these networks reflect, to a certain extent, the queued retransmission strategy described in [25].

TABLE 3—SUMMARY OF TIMELINESS ENHANCEMENT TECHNIQUES FOR COMMERCIALLY AVAILABLE INDUSTRIAL WIRELESS NETWORKS.

TECHNIQUE	WIRELESS HART	ISA 100.11a	IEEE 802.11	WISA
Ordered access	✓	✓	✓	✓
Frame prioritization	✓	✓	✓	✓
Improved retransmissions	✓	✓	✗	✓
Rate adaptation	✗	✗	✓	✗
Frequency diversity	✓	✓	✗	✓
Spatial diversity	✓	✓	✓	✓

Related Work

In this section, we review some interesting contributions to the field of industrial wireless communication systems from the scientific literature. Among the possible choices, the articles we present have been selected because they specifically focus on the timeliness aspects we have discussed so far. As the reader will notice, some of the these articles were cited in the previous sections, since it was necessary to refer to them in those contexts. They are recalled in this section for a more detailed analysis.

General assessments about industrial wireless communications are provided in [51] and [7]. In particular, among the topics addressed in [51], the author refers to both spatial diversity and interference mitigation, stating that they are techniques that face the core problem of industrial wireless networking, represented by the necessity of providing the required levels of timeliness and reliability. In the same direction, considerable attention to the adoption of wireless networks in industrial environments is paid in [7], which is specifically concerned with field-level communications.

A survey that focuses on IWSNs is presented in [52]. Among the several topics addressed by the authors, it is worth mentioning the quality of service that must be able to cope with the applications using these networks. In this context, timeliness often represents one of the most relevant requirements with which to comply.

Both [44] and [53] address the topic of hybrid (wired/wireless) industrial networks, in which the interconnection between wired and wireless network segments has a noticeable impact on the timeliness of the whole communication system. Specifically, [44] is a survey that generally addresses wireless extensions of wired industrial networks, whereas adoption of WLAN infrastructures in industrial environments is the focus of [53].

Timeliness, as we have seen in the previous sections, is strongly related to the MAC protocol parameters. An interesting example in this direction is provided in [18], in which the authors focus on the MAC layer of IEEE 802.15.4, pointing out the possible existence of an unreliability problem (and the consequent negative impact on timeliness) that may arise when the power management mechanism is enabled. In practice, when several nodes try to contemporaneously access the transmission medium, the delivery ratio becomes considerably low. The authors show that such behavior is caused by the CSMA/CA algorithm used by IEEE 802.15.4, particularly when power management is used in conjunction with the default parameter set recommended by the standard. For this reason, they suggest the adoption of an adaptive parameter setting strategy capable of coping with the network operating conditions as well as with the requirements of the specific applications.

Finally, we would like to present two application examples where timeliness enhancement is achieved by making use of some of the techniques described in [26]. The authors address the problem of providing real-time guarantees for messages delivered over wireless networks. Here they propose the adoption of a framework aimed at ensuring that the message deadlines are always matched. For a given set of messages characterized by some timing features (e.g., execution times, deadlines, periods, etc.), a truncated ARQ scheme (which bounds the number of transmission attempts), and a real-time scheduling analysis are combined in order to ensure that a message is retransmitted (after a failure) only if it does not affect the real-time guarantees of other messages. Clearly, with such a strategy, the packet error rate (PER) cannot be zero, since, in some cases, scheduled messages are not retransmitted at all. Nevertheless, the results provided (obtained through numerical simulations) show that the PER is kept at lower values with respect to the traditional retransmission strategies, while the bandwidth utilization is maintained at a good level.

The second application example is reported in [54]. Here the authors describe both the design and the implementation of a wireless fieldbus, providing an example of its application to the temperature monitoring of plastic machineries. The physical layer of the proposed network is based on IEEE 802.15.4, whereas the MAC protocol, which has been purposely developed, makes use of a hybrid access strategy. In particular, a TDMA technique ensures ordered access to nodes transmitting real-time data, while nonreal-time data (which are referred to as acyclic and used for network management in the article) make use of a CSMA/CA technique. In the practical application shown by the authors, a prototype network is used to acquire the temperatures measured by a maximum of 16 thermocouples. Each of these sensors periodically transmits three bytes (2 B for the temperature value and one status byte) to a central station. The minimum achieved period for the transmission of the temperature signals is 128 ms.

Conclusions

Today, wireless networks represent an appealing opportunity for industrial communication systems, since the benefits that arise from their deployment in this scenario are noticeable. These networks, however, have to cope with the severe requirements of industrial communication. In particular, they have to provide adequate timeliness.

In this article, we initially addressed some relevant issues concerned with the timeliness of industrial wireless communication systems, focusing on some general techniques that could be adopted to enhance it. Subsequently, we considered the most popular commercially available industrial wireless communication systems and investigated how they actually address timeliness aspects.

As it is well known, timeliness is negatively influenced by both the occurrence of transmission errors and the subsequent retransmission attempts, possibly interleaved by random backoff times. Thus, to achieve good timeliness, the first measure to adopt is, trivially, to ensure high transmission success probabilities, possibly on the first attempt(s). In this direction, ordered channel access and frame prioritization represent commonly available useful opportunities, since they basically limit channel conflicts and collisions with the consequent benefits on the transmission success probability.

Also, techniques such as frequency diversity and spatial diversity are revealed to be effective, since the former provides good immunity to in-band interference, whereas spatial diversity increases the packet transmission success probability through the use of either MIMO systems or cooperative networks. A further technique, namely rate adaptation, actually allows low PERs to be achieved. Unfortunately, rate adaptation may negatively impact timeliness, since the algorithm typically adopted by this technique (automatic rate fallback) can require a relevant number of transmission attempts to eventually come to the correct delivery of a packet. Consequently, we presented two alternative algorithms specifically tailored for industrial applications in that they ensure the number of retransmissions is kept very low. Furthermore, timeliness may be increased by the adoption of improved retransmission strategies that, as described, dynamically adapt the polling sequences in master–slave configurations, depending on the statistics of the transmission success probabilities of each polled device.

Among the commercially available industrial communication systems, we took into consideration Wireless HART, ISA 100.11a, and WISA, which implement, even if in different ways, most of the aforementioned timeliness enhancement techniques. In detail, the only exception is represented by rate adaptation, since, for these networks, there is no way to change the transmission rate.

On the other hand, IEEE 802.11-based systems, although not specifically conceived for industrial applications, natively offer a considerable set of opportunities to achieve satisfactory timeliness, even in this context, ranging from ordered channel access methods to automatic rate adaptation. Moreover, further improvements are envisaged in the future, deriving from the introduction of IEEE 802.11n systems. Indeed, the adoption of the full MIMO capabilities these networks are able to provide is expected to enhance timeliness, since it should significantly increase the first attempt transmission success probability. It must be considered, however, that the practical implementation of some of the proposed timeliness enhancement techniques requires direct access to the protocol stacks of the devices employed, to reprogram some of their low-layer primitives. Unfortunately, such an option is not commonly provided by the manufacturers of IEEE 802.11 devices.

It is also worth observing that, in some cases, a technique may complement others. For example, since the adoption of an effective rate adaptation algorithm ensures delivery of a packet with at most one retransmission attempt, in this case, the availability of improved retransmission strategies and/or spatial diversity may no longer be necessary.

As a final consideration, it is worth stressing the continuous need for experimental results. Indeed, particularly in the field of industrial wireless communications, the differences between the results derived from theoretical/simulation analyses and those obtained via practical experiments are often considerable [55]. In this context, the availability of real performance data represents a key issue, since, on the one hand, they reflect the actual behaviors of the communication systems, while, on the other hand, they may be used to tune the theoretical/simulation models to make their predictions much more realistic.

Acknowledgment

This work is supported by the Italian Ministry for University and Research (MIUR) research project PRIN 2009, “New generation hybrid networks in measurement and industrial automation applications—Characterization and wired/wireless perfomance measurement” (Contract 2009ZTT5N4).

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