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Analysis of the Limitations of WiFi Communications Managed by the IEEE 802.11 Protocol in Data Transmission in Automated Power Distribution Systems

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Abstract—This paper presents a study on the performances of the IEEE 802.11 protocol used in a Medium Voltage networks management system, carried out using a model for the simulation of WiFi chains architectures. The results of the simulations give some practical indications for the use of the IEEE 802.11 protocol also in presence of transmissions characterized by rigid time intervals, for which this protocol is usually not suitable. Finally the whole communications system is presented.

***Index Terms*—IEEE 802.11, WiFi, Diagnostic.**

I. Introduction

In [1] ÷ [5] an automatic Management System (MS) of a Medium Voltage (MV) network, both in regular conditions and in presence of a fault, has been presented. The MS is based on a diagnostic algorithm that continuously monitors a set of electrical quantities at every secondary substation.

The most efficient configuration of the MS comprises a central processing unit in the HV/MV station and local processing units in the MV/LV substations [6]. The units exchange data on the system status and, when needed, they command the tie-switches of the MV network at the secondary substations. In presence of a fault, the data and commands transmission, must be done in a very short time [7] (less than 1s). The substations at the ending buses of the faulted span send the diagnosis to the central unit of the MS, that elaborates the actions for an efficient service restoration procedure.

In [8], thanks to its limited cost and simplicity, the WiFi systems has been indicated as the most suitable for the on-line transmissions of the data and the commands of the MS. Nevertheless, the WiFi technology is based on the IEEE 802.11 protocol, that does not allow a deterministic evaluation of the data transferring times and is affected by a high delay in data transmission due to the data packet collisions. For these reasons, an analysis of the data receiving times both at the central unit and at local units can not be done following an analytical approach.

In this work, after a presentation of the IEEE 802.11 protocol and of its performances, both in a simple transmission between two WiFi stations, and in a transmission within a WiFi stations chain, are evaluated.

The transmission chain performances are also evaluated using a simulation model made on purpose, the results are presented varying the number of WiFi stations, the transmission rate, and the dimension of the data packet. Since the simulations highlight some of the weak points of the IEEE 802.11 protocol making it less reliable for the MS, suitable interventions for a more adequate utilization of it are proposed. Finally, the whole communication system is defined, some indications on the data transmission times are also given and suitable operative solutions are proposed.

II. The IEEE 802.11 Protocol

In the IEEE 802.11 protocol, all the information is divided into data packets or service packets. The data packets, whose maximum byte dimension is indicated by the protocol, are transmitted in succession.

The most used channel access type is a Distributed Coordination Protocol, DCP, adopting Carrier Sense Multiple Access, CSMA.

Every station that has data to transmit, checks the channel to determinate if there is a carrier. If the channel is free, the station sends its data packets (using the Mac Protocol Data Unit: MPDU).

If more WiFi stations find the channel free and they are so close that every station can listen to all the others, then the transmission can start in the same moment and data packets collide. In order to limit collisions, the IEEE 802.11 protocol establish that a station, after having found the channel free, does not start immediately the transmission, but after a waiting time T_{Wait}:

$$T_{Wait} = T_{Difs} + T_{Backoff} \tag{1}$$

Usually $T_{Difs} = 50\,\mu s$. Time $t_{Backoff}$ is randomly generated, following the expression below:

$$T_{Backoff} = \text{Random}[0 \div (CW - 1)]\, T_{Slot} \tag{2}$$

where $T_{Slot} = 20\,\mu s$.

The receiving station, after retrieving the correct packet, sends back, after t_{Sifs}, an acknowledge packet (Ack) in the time t_{Ack}. If the sending station does not receive Ack before Ack-Timeout expiration, it re-transmits the packet. The retry schema allows a maximum number of retries.

In (2) CW, starting from a minimum CW_{min}=32, is doubled till the maximum CW_{max}=256 at every retransmission of the same packet in the case of no reception of the Ack. Fig. 1 shows, as an example, the sequence of transmission operations in the case of 3 WiFi nodes (a, b, c), belonging to a group of nodes, not represented in the figure but all in the range of the transmission. It is hypothesized that two WiFi nodes (a and b) want to transmit to a third one (c).

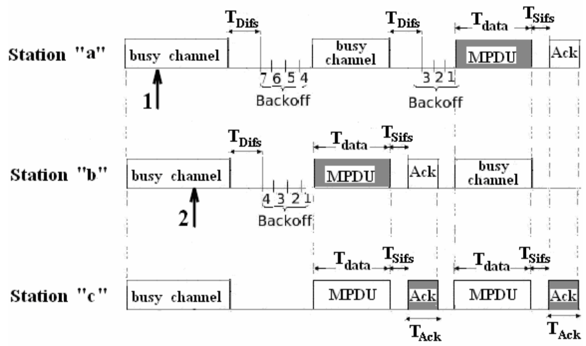

Fig. 1. Sequence of transmission operations in the case of three WiFi nodes.

The nodes a and b, that want to transmit towards c in the instants indicated by the arrows 1 and 2, find the channel occupied by other nodes and wait till it becomes free. As soon as it becomes free, a and b, after a time T_{Difs} draw, respectively, a value of CW comprised between 0 and 32 (being the first transmission of the packet). It is hypothesized that 7 is drawn for a and 4 for b. With these values expression (2) allows to find the corresponding $T_{Backoff}$. For both nodes, as the time passes, $T_{Backoff}$ is reduced of a quantity T_{Slot} until it becomes zero and the transmission starts.

In the case of Fig.1, at first $T_{Backoff}$ becomes zero for b that transmits the packet (the MPDU).

If the channel becomes busy again before the counting gets to zero, as it happens for a, the reached back-off timer value is frozen and the count starts again when the channel is free again, preceded by an interval T_{Difs}. Node c, after having received each data packet, waits a time T_{Sifs} and sends an Ack packet whose duration is T_{Ack} as confirmation of the reception. The sending time T_{data} of a data packet (MPDU) depends on its dimension in bit (Packet_data) and on the transmission rate "Data.rate", according to the IEEE 802.11 protocol (Tab. 1). The sending time T_{Ack} of an Ack packet depends only on the transmission rate "Basic.rate".

TABLE I. TIMES T_{ACK} AND T_{DATA}

Data.rate [Mbit/s]	1	2	5.5	11
$T_{data} = 192 + \frac{Packet\_data + 288}{Data.rate}$ μs			$T_{Ack} = 192 + \frac{112}{Basic.rate}$ μs	

III. PERFORMANCES OF THE IEEE 802.11 PROTOCOL

A parameter characterising the efficiency of the transmission is the time T_{send} with which the packet arrives to the receiving node successfully. Another parameter is the so-called throughput (Thr) defined by:

$$Thr = Packet\_data / T_{send} \quad (3)$$

A. *Transmission with two isolated nodes*

In the hypothesis that the system has only two nodes, the time T_{send} spent by a packet sent by the first node for reaching the second one, is given by:

$$T_{send} = T_{data} + T_{ack} + T_{Difs} + T_{Sifis} + T_{Backoff} \quad (4)$$

being the propagation time of the signal in the space negligible. For the Data.rate values prescribed by the IEEE 802.11 protocol and as the size of the Packet_data varies, in figures 2 and 3 T_{send} and Thr are reported. It has been assumed that Basic.rate=Data.rate.

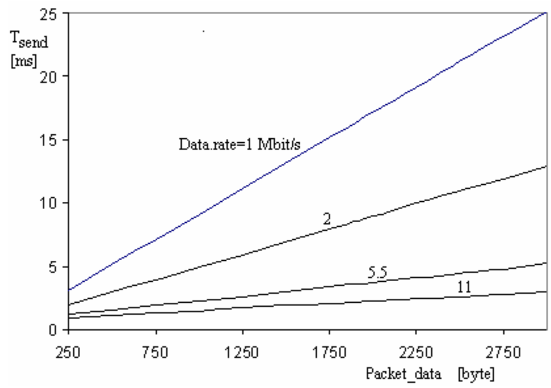

Fig.2 . T_{send} as function of Packet_data.

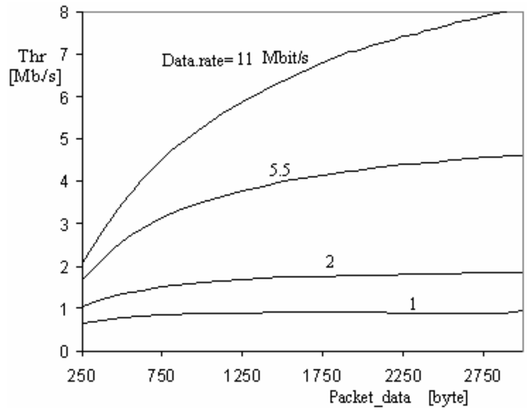

Fig.2 . Thr as function of Packet_data.

B. *Transmission along chain networks*

For sending information between two secondary substations far several hundred of meters, it is necessary to use many WiFi in series with secure range of 100÷150 m. The packets are sent in hop-by-hop mode, going towards the receiving node N, as represented in Fig. 4.

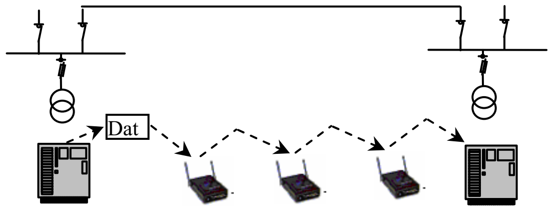

Fig.4. Transmission of the information with more WiFi nodes in series.

The minimum number of WiFi nodes condition implies that the range of a generic WiFi node reaches only the adjacent nodes (Tx_range =1). This means that the i^{th} node can listen to the nodes i-1 and i+1, but not to the nodes i-2 and i+2.

In this kind of networks, packets often collide and must be retransmitted. A first cause of collision is that two nodes decide to start their transmissions in two instants closer in time than T_{Slot}. In this condition, the second node is not acknowledged of the fact that the first node has started the transmission too and therefore they transmit at the same time.

The second cause of collision is the presence of the so-called hidden terminals. Fig. 5, representing three nodes (A, B, C) with Tx_range=1, clarifies this problem. If the node B does not transmit, nodes A and C, testing the channel and finding that it is free, can start the transmission at the same time. In this way, B receives simultaneously two packets that collide one with the other.

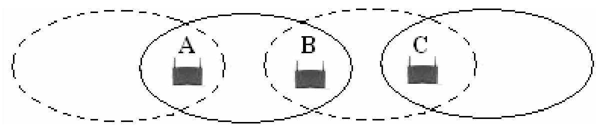

Fig.5. The hidden terminal.

Because of the presence of hidden terminals in a one-way transmission, the following possibilities of collision exist:

- when simultaneously node i sends a data packet towards node i+1 and node i+2 sends a data packet towards node i+3;
- when simultaneously node i sends a data packet towards node i+1 and node i+2 sends a data packet towards node i+1.

In order to evaluate the performance of a chain network, that depend on random mechanisms (Back-off procedure) and on the presence of the collisions, a simulation software must be used. In this work, the ECNS (Easy Chain Network Simulator), developed exclusively for chain networks and tested with NS-2 and WLAN, has been used. Using ECNS some simulations have been done varying the number of nodes and the Data.rate. The simulations have been done under the hypothesis that the starting node 1, after having sent a data packet with a positive outcome, has at its disposal another packet to be sent. In particular, the sequence of arrivals of the packet in the receiving node has been studied. In Fig. 6, the mean value T^m_{send} of the time intervals T_{send}, with which the packets arriving successfully to the receiving node N, is represented, as the number of nodes N vary, for every value of Data.rate prescribed by the IEEE 802.11 protocol and under the hypothesis that Packet_data=1500 byte.

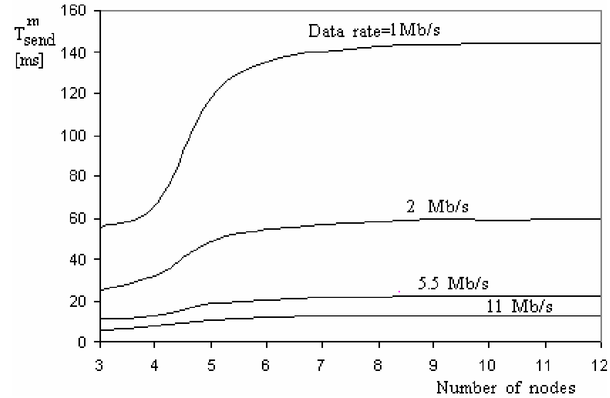

Fig.6. Mean Value of T_{send} as function of the number of nodes.

Under the same hypotheses, in Fig. 7, Thr^m, mean value of the throughput Thr evaluated for every sent packet, is represented as a function of the number of nodes for some values of Data.rate.

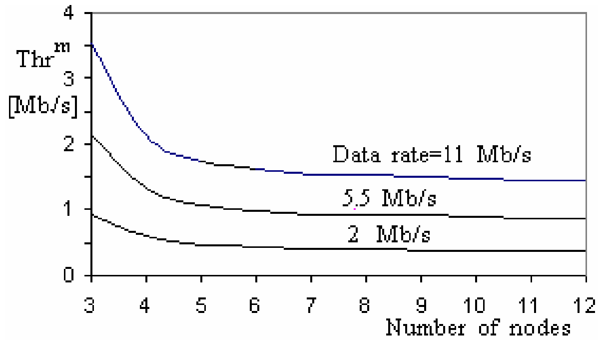

Fig. 7. Mean Value of Thr as function of the number of nodes.

From figures 6 and 7 can be deduced that collisions decrease the value of the throughput and increase the time between the reception of two different packets by the receiving station. A bidirectional communications with the same transmission frequency leads to unacceptable values of T^m_{send} and Thr if the data dispatch is done continuously, even if only in one direction.

IV. DRAWBACKS OF IEEE 802.11 IN THE USE OF CHAIN NETWORKS FOR ELECTRICAL POWER SYSTEMS MANAGEMENT

A first problem in the use of the IEEE 802.11 protocols for the diagnostic management of an electrical power system is that it would be necessary that the data packets arrive to the receiving node with almost constant time intervals.

However, in the analysis of the simulations done, it was shown that, at the mean values reported in figures 6 and 7, correspond significant excursion between minimum and maximum values of T^m_{send} and Thr^m. As a confirmation of this fact, under the hypothesis of Packet_data=1500 byte, Fig. 8 reproduces the graph of

T_{send}^{m} for Data.rate =2 Mb/s, comparing it with the minimum and maximum time intervals T_{send} with which the packets arrive successfully to the receiving node.

Since the receiving substation has to perform an on-line diagnosis of the status of the protected span of line, it is not acceptable that the time interval with which the data packets arrive can vary within the limits represented in Fig. 8.

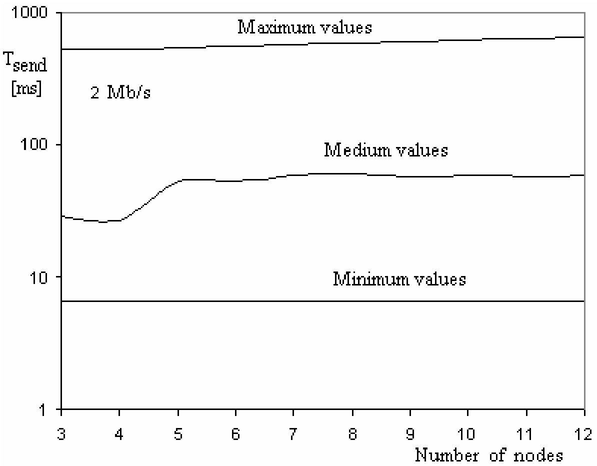

Fig. 8. Maximum, Mean and Minimum values of T_{send} as function of the number of nodes.

Another important consideration must be done about the time interval ΔT_s between the arrival of the generic data packet s-1 at the starting node 1, that saves it before it waits for the retransmission, and the arrival in the same node of the consecutive packet s.

Figures 6 and 7 have been represented in the case of variable ΔT_s, since the simulations are done considering that node 1 receives a new data packet after having sent with positive outcome the previous one. Therefore, the time interval ΔT_s depends on how much time is necessary for sending the data packet s-1, as function of:

- the values of CW at node 1;
- the occupation of the channel by node 2;
- the collision phenomena that force the retransmission of packet s-1.

The minimum value of ΔT_s corresponds to CW=0, channel 2 free and no collisions. In Tab.2 some values of the minimum ΔT_s, as function of Data.rate and for some values of Packet_data, are reported.

TABLE II. MINIMUM VALUES OF ΔTS [μS]

Data.rate / Packet_data	1 Mb/s	2 Mb/s	5.5 Mb/s	11Mb/s
500 byte	4.8	2.6	1,2	0,8
1500 byte	12.8	6.6	2,7	1,6
2500 byte	20,8	10.6	4,1	2,3

For a steady-state condition, the mean values of the ΔT_s related to the packets leaving node 1 do not have to be less than the mean value T_{send}^{m} with which the packets arrive successfully to node 1. Simulations have instead demonstrated the contrary.

And then, since in a time interval a number of packets greater than that arriving at node N leaves from node 1, overstocks occur at the intermediate nodes (in particular at node 2). Of course, for a transmission with a continuous dispatch of the packets, as it must be in electrical networks management, this condition can not be accepted.

V. A SOLUTION FOR THE MITIGATION OF THE DRAWBACKS OF IEEE 802.11 PROTOCOL

The aim is to manage the WiFi nodes so as to (see the system in Fig. 4):

- the sending frequency of the packets in the starting node corresponds to that of the packets at the arriving node and no overstocks occur;
- the difference between the minimum and maximum time of transmission of a packet to the node N is low.

For obtaining these results, having imposed the value of ΔT_s related to each data packet s equal to ΔT, some simulations have been done varying ΔT. As an example in Fig. 9 T_{send}^{m} as function of ΔT is reported, with Pachet_data=1500 byte, N=7 and Data.rate =11 Mb/s.

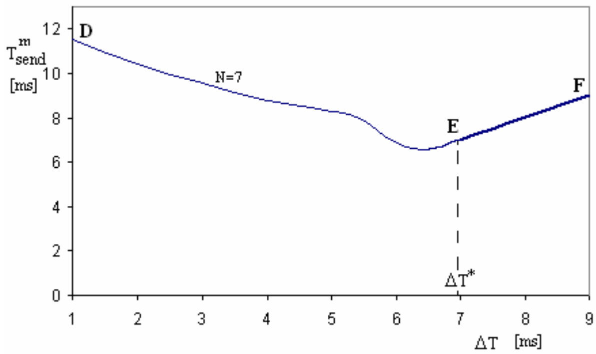

Fig. 9. Mean value of T_{send} as function of ΔT.

Fig. 9 shows that the trend of T_{send}^{m} is characterised by two parts:

- DE with $T_{send}^{m} > \Delta T$ where there is overstock of packets in the nodes upstream the arriving one;
- EF with $T_{send}^{m} = \Delta T$, without overstocks.

Of course, the maximum communication rate without packets overstock, is in the first part of EF, indicated with ΔT^*. For studying how ΔT^* varies as the number of nodes increases, in Fig. 10 the course of T_{send}^{m} deduced from Fig. 8 corresponding to N=7 nodes, has been compared with the courses corresponding to N = 3; 5; 12 nodes.

Fig. 10 shows that, if N>4, ΔT^* slowly increases as the number of nodes increases.

Sending packets with period equal to ΔT^* give a positive response also to the need of keeping low the difference between the minimum and maximum times of transmission of a packet to the node N. Indeed, Fig. 11 shows the maximum and minimum of T_{send}, with the mean value T_{send}^{m} in Fig. 9, with which the packets successfully arrive to N.

Therefore the difference between the minimum and maximum value of T_{send} strongly decreases when $\Delta T \geq \Delta T^{*}$, becoming acceptable for diagnostic communications in electrical networks.

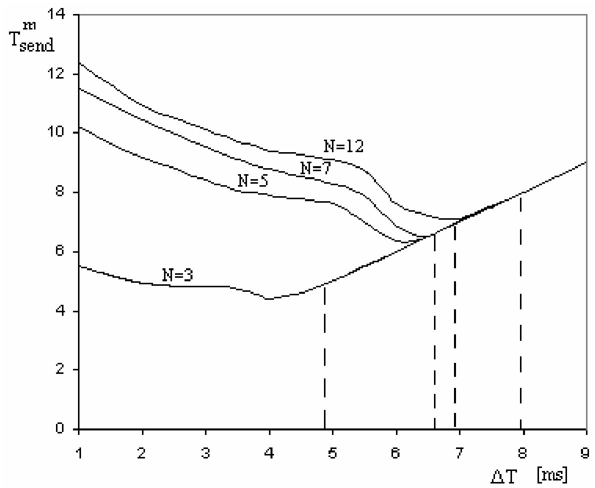

Fig. 10. Mean Value of T_{send} for various values of N.

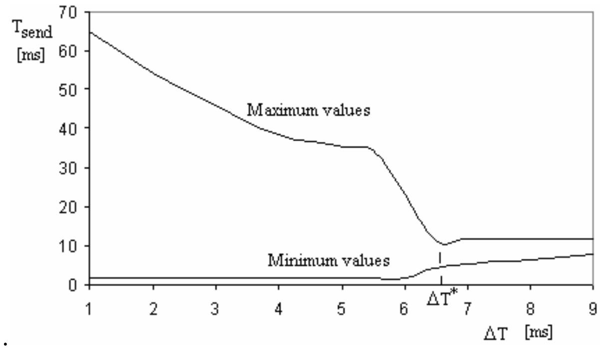

Fig.11. Maximum and Minimum Values of T_{send} as function of ΔT.

VI. The Communication System

Taking into account the considerations in the previous sections, the communication system has been defined. A MV line, radially managed, with two HV/MV stations at the extremity (A and B) is considered in Fig. 12.

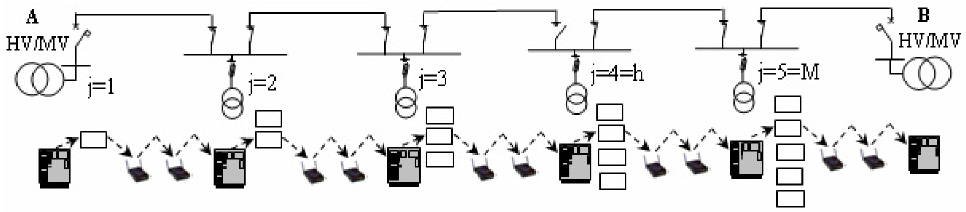

Fig. 12 Representation of the MV line.

A. Regular working conditions

In this case, the characteristics of the communications are the following:

- Every secondary station sends with regular time intervals towards one of the HV/MV stations (for example B), a packet containing the measured data. Transmission is unidirectional (from A to B) and the frequency of the radio signal is f_1.
- Station B sends the received data to the remote-control centre using a communications system different from WiFi.
- Station A, also communicating with the remote-control centre, transmits towards the secondary substations a packet for the variation of the network asset. This packet could be sent also from B with a different frequency f_2.
- The architecture in Fig. 12 allows the system to work also in presence of a fault in the transmission system at one of the HV/MV stations. Indeed, if a fault occurs in station B, the transmission direction of the data packets inverts and the eventual packet for the variation of the asset is sent by B with frequency f_2.

B. Fault in a span of line.

The characteristics of the communications are the following:

- Substation j, downstream the faulted span reveals the abnormal condition on the basis of the comparison of its data with those received by substation j-1 upstream the faulted span .
- Substation j opens the tie-switch downstream the faulted span and sends two command packets: the first towards A with frequency f_2, for opening the tie-switch in the substation j-1, the second towards B with frequency f_1, for closing the tie-switch in the boundary substation h.
- Substation j-1, once received the command from j, opens the tie-switch upstream the faulted span and communicates its status in the successive data packet sent to B.
- Substation h, once received the two packets, the first from j for command and the second from j-1 for confirmation of the opening of the tie-switch, closes the boundary tie-switch and restores the service.

In Fig. 11, in the boundary substation j=4, a tie-switch open for dividing the line into two radial ones is evidenced.

In the HV/MV station and in every secondary sub station a microprocessor and a WiFi node are installed. Along the line, various WiFi nodes are installed.

Station A and every other sub station, send toward station B a packet with the data of the measures done and the status of the station. Going towards station B, the number of data packet to be transmitted increases. Indeed from station A only one packet is sent. To the latter are added the other packets sent by the secondary substations. In this way, the last secondary substation has to send five packets.

In the following, with M and N are indicated, respectively the number of spans of the MV line and the number of WiFi nodes in a span.

In every communication cycle the secondary substation at the beginning of the span M must send in sequence N packets, each one containing the data from the substations upward. For this purpose, as input of its own WiFi node, the sub station will receive a packet every $\Delta T_M = \Delta T^*$. In this way, the time interval T_{cycle} with which the substation terminates the sending of all its data and of the substations upstream is given by:

$$T_{cycle} = M \cdot \Delta T_M = M \cdot \Delta T^* \quad (5)$$

In the same way, the generic substation j must send a sequence of j packets, each one related to all its data and of the substations upstream. For keeping the synchronism these packets must be sent in the same time interval T_{cycle} given by (5). Therefore the generic substation j will send a packet every:

$$\Delta T_j = M \cdot \Delta T^* / j \quad (6)$$

In this way, the time required by two consecutive substations to send the data is T_{cycle}.

The total time spent for completing the sending of a cycle of data from all the substations towards the HV/MV station is:

$$T_{tot} = M \cdot T_{cycle} = M^2 \cdot \Delta T^* \quad (7)$$

The time T_{com} necessary for sending a packet with an opening command to a tie-switch with a frequency f_2 from the substation j is equal to the value T_{send} evaluated in Fig.2. A command packet from a HV/MV station travels along the whole line in a time $M \cdot T_{com}$.

VII. Application Example

The line AB in Fig. 12, with 15 span, M=15 substations and N=5 WiFi nodes per span, is considered. In Tab. 3, for the Data.rate values of the IEEE 802.11 protocol and Pachet_data = 1500 byte, the values of the time interval characterizing the transmission are considered. The chosen ΔT^* must be higher than the values in Tab.3. The other relevant transmission parameters are widely acceptable.

TABLE III. Result of the simulation

Data.rate [Mb/s]	ΔT^* [ms]	T_{cycle} [s]	T_{tot} [s]
1	58	0.87	13.1
2	30	0.45	6.7
5.5	12	0.18	2.7
11	6.6	0.1	1.5

VIII. Conclusion

The performances of the WiFi communication system to be implemented for an automatic management of the MV networks have been studied. With this purpose, with a suitable simulation model, the behaviour of the IEEE 802.11 protocol has been studied, and its very low reliability has been appreciated. It has been shown that this protocol can be used for power systems diagnostic applications only if the transmission time of the data packet is higher than ΔT^*. The design of the whole communication system has lead to the definition of some parameters for the evaluation of its efficiency. An application example has highlighted that the proposed values of ΔT^*, T_{cycle} and T_{tot} are widely compatible with the diagnostic management of the faults with innovative strategies.

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该套课程全面讲授了当前手机天线相关设计技术，内容涵盖了早期的外置螺旋手机天线设计，最常用的几种手机内置天线类型——如 monopole 天线、PIFA 天线、Loop 天线和 FICA 天线的设计，以及当前高端智能手机中较常用的金属边框和全金属外壳手机天线的设计；通过该套课程的学习，可以帮助您快速、全面、系统地学习、了解和掌握各种类型的手机天线设计，以及天线及其匹配电路的设计和调试...

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WiFi 和蓝牙天线设计培训课程

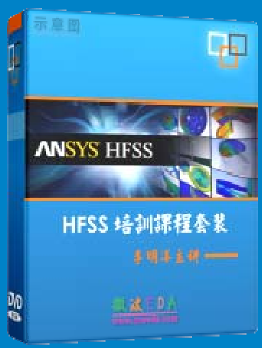
该套课程是李明洋老师应邀给惠普 (HP)公司工程师讲授的 3 天员工内训课程录像，课程内容是李明洋老师十多年工作经验积累和总结，主要讲解了 WiFi 天线设计、HFSS 天线设计软件的使用，匹配电路设计调试、矢量网络分析仪的使用操作、WiFi 射频电路和 PCB Layout 知识，以及 EMC 问题的分析解决思路等内容。对于正在从事射频设计和天线设计领域工作的您，绝对值得拥有和学习！…

课程网址：http://www.edatop.com/peixun/antenna/134.html

CST 学习培训课程套装

该培训套装由易迪拓培训联合微波 EDA 网共同推出，是最全面、系统、专业的 CST 微波工作室培训课程套装，所有课程都由经验丰富的专家授课，视频教学，可以帮助您从零开始，全面系统地学习 CST 微波工作的各项功能及其在微波射频、天线设计等领域的设计应用。且购买该套装，还可超值赠送 3 个月免费学习答疑…

课程网址：http://www.edatop.com/peixun/cst/24.html

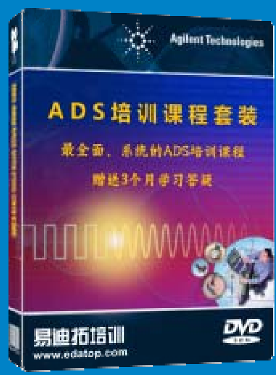


HFSS 学习培训课程套装

该套课程套装包含了本站全部 HFSS 培训课程，是迄今国内最全面、最专业的 HFSS 培训教程套装，可以帮助您从零开始，全面深入学习 HFSS 的各项功能和在多个方面的工程应用。购买套装，更可超值赠送 3 个月免费学习答疑，随时解答您学习过程中遇到的棘手问题，让您的 HFSS 学习更加轻松顺畅…

课程网址：http://www.edatop.com/peixun/hfss/11.html

ADS 学习培训课程套装



该套装是迄今国内最全面、最权威的 ADS 培训教程，共包含 10 门 ADS 学习培训课程。课程是由具有多年 ADS 使用经验的微波射频与通信系统设计领域资深专家讲解，并多结合设计实例，由浅入深、详细而又全面地讲解了 ADS 在微波射频电路设计、通信系统设计和电磁仿真设计方面的内容。能让您在最短的时间内学会使用 ADS，迅速提升个人技术能力，把 ADS 真正应用到实际研发工作中去，成为 ADS 设计专家...

课程网址： http://www.edatop.com/peixun/ads/13.html

我们的课程优势：

※ 成立于 2004 年，10 多年丰富的行业经验，

※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求

※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

联系我们：

※ 易迪拓培训官网：http://www.edatop.com

※ 微波 EDA 网：http://www.mweda.com

※ 官方淘宝店：http://shop36920890.taobao.com