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Survey on performance analysis of embedded and conventional networks.

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***Abstract*— End to end cross-domain network communications (personal area network to a local area network, etc.) can be achieved in different ways. This does not necessary mean it is done efficiently. We believe that the interconnection end to end performance depends on factors such as framing, encapsulation, MAC layer protocols, transmission channel and queuing disciplines. This survey presents the main research works on these factors considering two scenarios: i) isolated domain communication and ii) interconnected domain communication (heterogeneous networks). Cross layer design is then presented as a key player to obtain optimum end to end performance. Open research questions in this matter are finally discussed along with possible solutions considering all factors as a whole within the performance model.**

Keywords— mac protocols, framing, channel models, queue models, network performance, cross-layer.

I. Introduction

Today's networks are formed besides conventional computers, by sensors, actuators, personal digital assistants (PDA), mobile phones, and many other embedded systems. This diversity can be explained by the interconnection of embedded system networks (ESNs) to traditional computer networks (conventional networks). These applications are domotics, automotive control, sensor networks and surveillance, etc. ESNs include protocols such as controller area network (CAN), local interconnection network (LIN), FlexRay and PCI Express for the wired networks and ZigBee and Bluetooth for wireless.

Some applications require information to be transmitted beyond their own network domain. This is done by the use of bridges, gateways, routers, among other devices. These network elements implement the necessary framing encapsulation, media access protocols, queuing disciplines, routing algorithms.

The framing is the process in which bits stream from the network layer is divided into groups of bits or data units for transmission in a channel. This process includes a frame header which affects the data throughput.

Encapsulation is the technique in which a packet from one protocol is placed within the data field of the packet of another protocol. This procedure like framing, adds a header which also affects throughput. A packet with a large header and a short data field will cause a low throughput and, in the other hand, a large data field can cause a greater delay and error probability. Some researchers have treated the packet size trouble with the aggregation techniques obtaining lower delay (25% to 50% delay reduction) and 7% to 9% increased throughput using different packet sizes [4].

The media access protocols are used to provide control of the channel access and utilization, including procedures to detect which in some cases correct packet errors. The authors in [22] studied the CSMA-CA performance and combining it with a distributed back-off strategy regulated by the link quality, they obtained a 69% higher goodput and 154% more data bits per energy unit in a IEEE 802.15.4 network.

A channel model is an analytical representation of the communication media. It helps to analyze a whole network or complement a more complex model.

The queuing theory is a powerful tool for network analysis, it allows to view in an analytical way the network behavior. Also performance models are mathematical representations of the communication systems. In many cases the are conformed by the channel, queue, protocol and other mathematical models.

This survey shows the performance analysis of some techniques impacting on the communications performance. Section II describes the key factors that, in our consideration, are the major influence in the network performance. Section III shows some analytical tools. Section IV introduces some concepts and works about cross layer design. Section V describes the two mentioned above interconnection scenarios. Section VI discuss the open research questions. Section VII shows our conclusions about this topic.

II. The key factors

A. Framing

Taking into account variables like the back-off process time, success and collision time and their probabilities, the authors in [18] calculated probability distribution of the 802.11 MAC layer service time. They assume that the collision and success times depend on the transmission rate, the length of the packet and overhead, and the specific transmission scheme.

Korhonen and Wang [19] present a mathematical model which shows the relation between the packet length and the total delay in 802.11. They assume the bit errors occurs in bursts so they formulated the probability of at least 1 bit error in a packet of length l, as: $p(l) = 1 - e^{-\lambda l}$ where $1/\lambda$ is the average number of bits between two error bursts, and the packet error rate. With b as the probability of that a bit is transmitted in a error burst as:

$$p(l) = b + (1-b)*(1- e^{-\lambda l}) \quad (1)$$

Finally, they formulated the total overhead R in function of the packet header and payload sizes and using (1) as follows:

$$R(l) = (h/l) + [p(l) / 1-p(l)] \quad (2)$$

Where the first term in (2) is the packet overhead and the second one is the average number of retransmissions to deliver a packet reliably. Then, by differentiating the (2) equation (when the value of (1) is known) they find the minimum overhead and delay.

B. *Encapsulation*

The encapsulation process have an important impact on the upper layers performance because it implies fragmentation, smaller packet sizes than the upper layers, physical layer characteristics, etc. In [20], Filali models the effect of the native 802.11 fragmentation in the TCP transmissions, he take into account many parameters as the end-to-end packet loss, the maximum number of retransmissions, the number of fragments and the bit error rate (BER) to construct a model. The probability of success transmission of a given fragment is formulated with the unsuccessfully transmission probability of the current attempt. The model can be used to determine the best frame quantity considering the traffic load and TCP packet sizes.

Vu et al [23] shows a mechanism to dynamically adjust the packet size based on the BER. They propose to reduce the packet size, when a bit error occurs then the procedure reduces the packet size to increment the transmission success probability. But this approach not always works in an optimal way, therefore the transmission will be interrupted temporary to reduce the loss rate and the power consumption. And as a disadvantage, this mechanism can cause increased system delay or transmission time.

The authors in [24] propose to calculate a fixed optimal packet size based on the BER, the burst error rate, the start-up energy consumption and the useful energy of the communication of a bit. With this approach they get a 15% more efficient power consumption.

There are other way to improve the performance of the encapsulation, the packet aggregation. This procedure adds various small packets from one protocol into other protocol payload field. All the smaller packets are transmitted as a single PDU (Protocol Data Unit). This method can increase the throughput under certain conditions, but if the aggregation is not controlled, it can be a problem to obtain a better performance. If the amount of aggregated packets is so small, then the method will be inefficient, because the added overhead causes low throughput. In the other hand, if the number is bigger, then the service time will be the problem.

Using a Markov chain to represent the packet encapsulation and aggregation Jung et al [2] measures the performance of this procedure in a general way. For the analysis, they consider the aggregation process in a frame with a fixed length header, and a variable number of aggregated packets. From the same model, they can obtain the probability of n packets aggregated, the average number of packets, and the total and average delay times. Through various experiments, they conclude that is possible (in the analytical model) to find the number of packet with minimum total delay. Besides, when the number of packets are less than the optimal, the overhead causes more delay. In the other hand, when the number of packets is greater than the optimal, increases the delay because it takes more time for the transmission.

Thourrilhes [4] studies the effect of aggregation in wireless networks. He shows that with a data packet size varying between 0 and 2000 bytes (a small packet), and considering various traffic types, (including TCP transmission, voice and multimedia traffic) grouped into a single frame improves the throughput and latency in comparison with the transmission of the small packets in a normal way.

In some cases, the above schemes are inadequate because they are fixed. Then, an adaptive scheme that modifies the aggregation rate depending on traffic, node number, etc. allows a better performance and lower system delay.

The frame size adaptability can be achieved by taking into account some factors like the BER. The authors in [8] use this factor to determine the optimal aggregated frame size in 802.11n wireless local area networks. By concatenating several MAC service data units in the data field of an MAC protocol data unit (A-MSDU) or aggregating the complete MSDU with its header to conform a sub-MPDU (A-MPDU) as the aggregation techniques. With from the BER for the each aggregated packet, they obtain the error probability for all packets included in the PDU. From that factor and the collision probability, they obtain the transmission probability in a contention window. The analysis shows that the optimal aggregated packet size is very sensitive to the BER. They conclude that their adaptive aggregation schemes has better throughput than the fixed and randomized aggregation.

Chen et al [3], describe a scheme for a clustered wireless sensor networks. The adaptation consists in the adjustment of the aggregation rate and the node reporting frequency depending on the number of sensors. The sink node reconfigures the two parameters mentioned before in the cluster heads and the final nodes, estimating the new values with the data collected previously. The performance analysis is focused in the algorithm convergence (to obtain the equilibrium between sensing frequency and aggregation rate) but the delay and throughput is not analyzed. The scheme converges at 5 time units in the worst case.

C. MAC Protocols

We divide the impact of the MAC protocols on the transmission performance into i)channel access policies, ii) scheduling and iii) error control.

The throughput in multihop ad-hoc networks is analyzed by the authors in [28]. They modeled a general framework to fit MAC protocols like the RTC/CTS mode of 802.11. They validate the analytical model by simulating of two different routing algorithms: the Most Forward with fixed Radius (MFR) and Random Forward with fixed Radius (RFR), as MAC protocol RTS/CTS mode of 802.11 DCF with busy-tone. They do not consider any channel conditions.

Otal et al [25] proposes a distributed queuing protocol for wireless sensor networks that enhances the performance in a 15% with small packets and 45% for larger packets. Also is 50% more energy efficient than 802.15.4. Other characteristic to save energy in this kind of networks is the NACK (non-acknowledgment) mode. By eliminating this communication control characteristic, the number of transmissions is reduced, but the errors cannot be detected. In [26], Shu et al analyze this condition trough a 3D Markov chain that yields the packet loss statistics. They verified it with a NS-2 simulation yielding similar outcomes. They conclude that packet loss is considerable in the NACK configuration being the cluster size and the message length a significant influence.

The error control is revised by Vuran and Akyidiz in [27] with a cross layer approach. They compare the forward error control (FEC) and Automatic Repeat Request (ARQ) making a model in function of the end-to-end energy consumption, latency and packet error rate (PER). The analytical results shows that when the routing protocols are focused on reducing the transmit power, the ARQ protocol have less latency, but the FEC scheme are better energy saver. But when the routing protocols are focused on extend the hop length, the FEC schemes has less latency and energy consumption.

D. Channel Models

Lal et al [13] proposes a link model included in a metric to measure the link quality. Their model represents a channel BER effects in the transmission of a packet with L bit length including 2 bytes length header. With the condition that the header bytes must be received with no errors and the remaining bytes with at most one bit error, they defined the channel model as the probability of any bit error in the channel.

After the Lal's work, Zuniga et al [14] complement the model including the signal-to-noise ratio (SNR) when the measurement of the BER is not available. They add the distance between nodes and the noise floor factors to get a more real channel model, then; the error probability parameter is more accurate. They also give the parameters for various channel modulations and encodings.

Another works are focused on the BER process only. The authors in [15] made an experiment to assess the BER in CAN networks. Setting 3 environments (benign, normal and aggressive) they obtained the BER and the packet inconsistency probability for the three cases.

In comparison, the authors in [16] use the BER parameters to model the 802.15.4 and 802.11 channels to study the mutual interference, given that the two networks use the 2.4 GHz band. With the inter-arrival times and the BER they obtain the collision time for both networks. The PER is obtained in function of the BER and the collision times to complete the interference model. The throughput is calculated using the parameters mentioned above. Similar work is done in [17] but the interference model is proposed with 802.15.4 and 802.15.1.

III. Analysis tools

A. Queuing Models

Kibria et al [11] uses an M/G/1 queue to represent the Bluetooth multipoint communications, using head-of-the-line queuing discipline to prioritize the different traffic types and then they calculate the waiting time, the throughput and the packet loss.

Zhai and Fang [18] modeled the service time distribution and assuming a Poisson process, a buffer on each station of size K and each station as a single server, they represents transmission process as an M/G/1/K queuing system. Their analysis shows that in a non-saturated traffic scenario, the performance depends only on the total traffic and in the saturated case the performance depends on the number of stations.

The authors in [12] use a Markov chain to represnt the link availability, associating a BER level with each state in the chain, setting the state 0 as the unavailable link with the maximum BER level. Their analysis includes the packet error rate and the mean packet delay. They compared the analytical model with an AdHocSim and OMNet++ simulation and they obtained similar results.

Chang et al [7] uses a Markov chain model to represent a Wi-Max network and measure the delay caused by the polling procedure. Taking the number of stations served as the states in the Markov chain, they can obtain the expected number of nodes. By combining it with the number of polls and all transmission process delays, they calculated the average polling delay. Once the delay is obtained, they can formulate the network throughput.

The authors in [2] represents the encapsulation and aggregation process with a Markov model to analyze delay and throughput. Assuming the inter-arrival time of the packets are exponentially distributed and stored in a infinite buffer, and the packet size and the transmission time has a phase-type distribution, resulting in a complex quasi birth-death Markov chain.

B. Performance Models

The delay and throughput are the principal metrics for expressing the networks performance. The delay can be expressed also in several ways depending on the measured segment, the direction of the transmission (i.e. if the transmission is analyzed in unidirectional or bidirectional way). But to know the acceptable delay is a very hard work, given that each network has several different conditions, technologies and techniques to transmit and control the data.

In [5], Goyal et al propose techniques for determining the upper boundaries for end to end delay in heterogeneous conventional networks. They classify the queuing algorithms used in the network's switching elements in a class that have “guaranteed rate” conditions, in other words, the algorithms must assure the expected arrival times based on the packet rate, the packet length. In this class are grouped algorithms like virtual clock, PGPS and SCFQ. Then, they develop a method, based on the affirmation that all guaranteed rate algorithms have a predictable arrival time plus the service time and the propagation delay between the servers and the client stations.

The the best values for the performance can be obtained by maximizing or minimizing some variables of the network. In [23] Madan et al proposes a cross layer design to minimize the power consumption in WSN taking into account a routing flow, link schedule and link transmission power for all active time in TDMA. Modeled as a convex problem they optimize the transmission power, rates and link schedule, to maximize the lifetime of the network.

IV. Cross Layer Design.

The OSI reference model divides the networks into functional layers and this allows analyzing, designing and constructing the networks in an easier way. But this division imposes a flexibility restriction because each layer must be communicated only with the adjacent layers. A recent approach is to analyze and to design the communication systems by violating the OSI model restrictions by communicating non-adjacent layers, merging two or more layers or creating a shared database among the seven layers [21], that is the cross layer design (CLD).

In [22] the authors propose an improvement of 802.15.4 by a CLD approach. By calculating the BER of the link in each node and depending on this value, they select the back-off interval. With this approach they obtain up to 69% higher goodput and 154% in the bits per energy unit probing that the flexibility provided by CLD allows the enhancement of the actual techniques.

In [30], the network utility is maximized through non convex problem formulation. The authors consider the roting, medium access control and the energy distribution of a multihop wireless network. These factors are the constraints of the proposed cross layer optimization problem.

The energy is an issue on the WSN too. Karimifar and Cavers [31] uses this factor and the layer 2 scheduling as constraints of the data volume optimization problem. They conclude that for the data volume optimization, the best transmission policy is to transmit sequentially. Similar work is done by the authors in [32]. By using a simple MAC protocol and routing information, they intend to reduce congestion and improve the energy usage and delivery ratio. They achieve it by grouping nodes into trees rooted from sink node and assigning different transmission schedules.

Based on the NUM (network utility maximization) framework, Ren *et al* [33] proposes two optimization schemes: i) joint congestion and medium access control scheme and ii) joint power and bioeffects control scheme. The last one introduces the biological effects caused by high power radio frequency to evaluate and control this specific factor.

Although many authors does not mention in specific way, they take advantage of the flexibility of working with the CLD approach.

V. Domain Interconnection

The isolated domain case is widely studied, but the interconnect domains forming an heterogeneous network is a specially interesting case. The next two sub-sections explain two different interconnection scenarios, but can be viewed one as a special case of the other, given that both scenarios can use the same techniques. The unique difference is the end node, in one case the same original domain type and different type in the second case.

A. Extending domains with another different domain

Using one domain (generally a conventional domain) to extend another domain (conventional or embedded) as a backbone to expand the second domain capabilities is a common practice. Using, for example WiFi to extend the wired network in areas where is impossible to deploy a wired system in conventional domains is a common practice.

Bayilmis et al [1] use this idea to interconnect two CAN segments through an 802.11 link, putting the CAN packet into the 802.11 payload field (Fig 1).

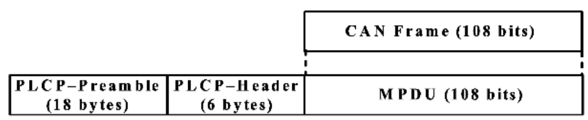

Fig 1. The encapsulation process

Using a look-up table the bridge make a decision if the packet is forwarded to another segment or is dropped because is for the local segment. The performance measurements where done in two ways, end to end delay under varying loads and the forwarding rate (the transmission from one port to another in the bridge) measurements, but they only use this measurements to prove that the messages are delivered from one can segment to another within the Society of Automotive Engineers delay limits.

Similar work is presented by Leal et al in [9] where they proposes a gateway between WiFi and Zigbee to use the WiFi networks as a backbone to interconnect the Zigbee segments. In their ongoing work, they mention that the initial implementation is an interface between the two domains using a proxy table for each domain (like the look-up table in [1]) to maintain the node list.

Other work related to this topic is proposed by Wang et al in [10], where the authors uses a network architecture conformed by a wired Ethernet backbone extending wireless Ethernet segments, focusing their analysis on the fairness of the end-to-end sessions. By posing the problem as a non-convex and non-separable optimization problem, they obtain an algorithm and the parameters to modify the protocol parameters in transport and link layers, modifying the end-to-end session rates and the scheduling rates respectively

B. Interconnecting different domains

To interconnect two different domains, several factors must be taken into account, like the protocols in two domains, the frame size, etc. The simplest way is taking the payload or even the whole packet of one protocol into the payload of another protocol. This network architecture generally uses the same techniques that the domain extending architecture.

Beside, in [29] the authors proposed architecture for interconnect heterogeneous networks. This architecture is intended to provide end-to-end communication to heterogeneous devices and networking technologies and hide the network complexity, through a connectivity abstraction and a naming framework respectively. The architecture enables the communications with advanced capabilities like dynamic binding, indirection, delegation and bridging, independently if the communication technology is packet or circuit based, if is actual or legacy, wired or wireless, etc.

VI. Open Research Questions.

Although there are a lot of researches about network performance taking into account different metrics and parameters, to the best of our knowledge, these works does not include performance analysis for the different domain interconnection.

The inter-domain connection mathematical models will be more useful if is included the end-to-end performance analysis because the network is better represented and can be enhanced more accurately.

The inclusion of the four key factors and using the analysis tools mentioned in this survey in a networking model with a cross layer approach will provide more flexibility in the analysis and design of heterogeneous networking devices and scenarios.

In our research we will combine all this factors to study the behavior of the end to end communications in the two scenarios mentioned above. Posing the network end to end connections and characteristics as a mathematical model we can observe the actual performance. After that we can optimize the model to obtain the best performance of the interconnections to get a better throughput and lower system delay.

VII. Conclusions

In this survey we show some works that studies in different ways the network performance. We believe that taking into account the effects of framing, encapsulation, the MAC protocols and the transmission channel characteristics the performance can be improved. Using the analytical tools mentioned above, we are modeling the above network characteristics to study their relation and the impact on the network performance with a cross layer approach. With this approach, the analytical model will have more flexibility and will permit to analyze the entire network as an identity.

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