QoMOR: A QoS-aware MAC protocol using Optimal Retransmission for Wireless Intra-Vehicular Sensor Networks

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***Abstract*—The paper proposes a MAC layer protocol called QoMOR (QoS-aware MAC protocol using Optimal Retransmission) that is designed to provide QoS in a decentralized network with multiple sensor (source) nodes that do not have the capability to receive acknowledgements from the sink node. A minimum data delivery probability between the sensor and sink nodes is achieved by allowing each source node to transmit each new packet an optimal number of times in every interval of time. The paper first discusses the single QoS class case and derives the maximum achievable frame delivery probability and then extends the concepts to the multiple QoS class case. It also addresses a few design optimization criteria. Simulation and numerical analysis results show that QoMOR can effectively provide QoS guarantees under distributed control without using conventional ARQ-based schemes.**

I. Introduction

The current automotive sensor networks are wired systems. A normal vehicle may have more than a hundred sensors and switches. Driven by the safety and environmental issues such as the need for stability and emission control, more sensors are being added to vehicles [1]. The wiring harness of the sensors contributes to at least 60 lbs of normal vehicle weight. To reduce the vehicle weight and the cost of wiring harness, it is desirable to replace signal wires by wireless links. To design an optimal wireless intra-vehicular sensor network, it is critical to investigate medium access control (MAC) protocols so that the performance with respect to latency and reliability is the same as that achieved by the wired sensor network. Researchers at Hughes Research Lab and General Motors Corp. have evaluated the MAC protocols in the IEEE 802.15.4 standard with respect to its suitability for use in prospective wireless intra-vehicular sensor networks [2]. They quantified the latency performance of the IEEE 802.15.4 MAC and concluded that it cannot support the sub millisecond latency requirements.

Based on the low cost and high energy efficiency requirement of sensors, we think it is reasonable to assume that the sensors in the intra-vehicular networks have only the transmitter function, but no receiver function, i.e. sensors cannot receive any signal from electronic control unit (ECU) for synchronization and scheduling. This network model implies that the conventional ARQ or scheduling schemes cannot be applied in the MAC protocol. Also, many contention-free multiple access schemes investigated in, for example [2], do not work in this setup. Our goal is to develop a de-centralized MAC protocol to provide QoS guarantees for both time-critical and non time-critical sensor readings. This is a challenge that has not been adequately addressed by any existing approach.

The most important metrics to analyze the QoS performance of any MAC protocol are throughput, latency and delivery probability. However for the wireless intra-vehicular sensor network that we are considering, we will focus on the frame delivery probability as the metric. This is because the traffic load is fixed (as each sensor generates one frame of a fixed size every T units of time) and usually low (e.g., 32 bits every 1 ms per sensor). Also, the latency of a successfully delivered frame is bounded by T (as a frame that cannot be successfully delivered within T is simply dropped). Accordingly, the resulting throughput in the network can be calculated based on the product of the delivery probability and the traffic load while the latency is randomly distributed in the interval $(0, T]$.

In this paper, we have designed a MAC protocol and studied its performance assuming that the wireless intra-vehicular sensor (WIVES) nodes belong to either single or multiple QoS classes with different delivery probability requirements but share the single communication channel. The study shows that, given requirements of a minimum network size of 100 nodes and $1msec$ latency, our approach can achieve the delivery probability of 0.977 for the single QoS class case and 0.998 for the two QoS classes case, assuming the higher priority class has 30 nodes and the lower priority class has 70 nodes. However, the study also shows that the requirements for certain mission critical sensors which require that the probability of message failure be less than 10^{-8} cannot be met. To achieve these stringent QoS requirements and as a future extension of this work we intend to study the protocol for the multiple channel case considering the intra-vehicular sensor network as a multichannel DS/SS ALOHA system and also design a hybrid-MAC protocol which will support a few special nodes equipped with receiver modules.

The rest of the paper is organized as follows. Section II describes background information on UWB technologies for WIVES nodes. Section III formulates the problem, a few de-

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sign objectives and describes the general idea of the proposed approach. Section IV and Section V present the theoretical analysis and simulation results for the proposed MAC protocol called QoMOR for the cases of a single QoS class and multiple QoS classes respectively. Section V-B presents an algorithm for solving one of NLIP problems defined in Section III. Section VI concludes the paper.

II. Background: UWB Technologies for WIVES nodes

For wireless sensors in automotive vehicles, ultra-wideband (UWB) technology is the most promising among all possible technologies. The FCC Part 15 Section 15.503 definition of a UWB transmitter is, "An intentional radiator that at any point in time, has a fractional bandwidth equal to or greater than 0.2 or, has a bandwidth equal to or greater than 500 MHz, regardless of the fractional bandwidth." Several vendors including Freescale offer UWB chipsets and at the 2006 Consumer Electronics Show, consumer electronic devices employing UWB were displayed. UWB is capable of supporting applications that include high power military applications [3] to low power uses in vehicles [4], [5], laptops and medical RFID systems.

Direct sequence UWB technology is the best to resolve multipath of a communication signal reflected in the semi-closed metal environment within an automotive vehicle. This super resolution of multipath provides stable signal without fading and high capacity in wireless communications [4]. It simplifies receiver design and implementation and leads to lower receiver cost. The large bandwidth of direct sequence UWB technology provides the best performance in the presence of intentional and unintentional interference and makes it a good fit for the application of intra-vehicular sensor networks where low power and signal reliability are critical. The feature of super multipath resolution is not available from any of the existing wireless technologies.

A UWB testbed has been built at Oakland University to characterize intra-vehicular RF communication channels [4]. Extensive RF propagation measurements within vehicle settings have been performed. In particular, the UWB testbed has been applied to measure signal propagation in a 1999 Chevy Prism Sedan, with the hope to replace the water-tight twisted wires and connectors in the 4-channel anti-lock braking systems (ABS), and in the engine compartments in the first phase. Summarizing the data collected for a 1999 Chevy Prism Sedan using UWB, one can conclude: (1) Communications between a transceiver at the bottom of the engine compartment and rear wheel speed sensors can be achieved at 330 mega-pulses per second using UWB technology without inter-symbol interference (ISI); (2) When the hood is shut, UWB communications within the engine compartment can achieve 476 mega-pulses per second without ISI when there is a line-of-sight, or 50 mega pulses per second without ISI when there is no line-of-sight; (3) The received signals for UWB communications within the vehicle are very stable, and have negligible fading; (4) Pulses traveling through different paths are distinct in the received signals. In other words, the UWB technology has resolved multipath. Therefore, UWB can provide sufficiently high data rate for hundreds of wireless sensors in future automotive vehicles. The negligible fading in the received signals makes it much easier to design transceivers with lower cost and complexity.

The measurements have been used to derive a mathematical model of the wireless communication channel. The mathematical model and understanding of the intra-vehicle RF propagation channel will enable the design of a robust UWB communication system in an intra-vehicular setting. Channel impulse response functions for critical intra-vehicular communication links have been obtained. These links are for the communications between the electrical control unit (ECU) located within the engine compartment and sensors located in a variety of spots inside a vehicle, such as, ABS sensors on wheels, engine sensors, sensors inside the passenger compartment etc. The channel measurements and modeling have laid a foundation to design and build intra-vehicular UWB sensor networks at low power and low cost. The results have shown that UWB can help to convert a fading channel using narrowband/broadband wireless technology to a distinct multipath channel with no fading. If the fading could not be handled, it would be too costly and impractical to have wireless links for sensor communications in vehicles.

The automotive industry needs MAC protocols to guarantee that at least one message from every mission critical sensor must be successfully received by the central receiver on the ECU in every $T = 1ms$ for real time control and computing. The probability of message delivery failure from each transmitting sensor to the receiver within $T = 1ms$ is required to be $P_f < 10^{-8}$. The transmission power of each sensor must be minimized to maximize the battery life. The protocol is required to support at least 100 sensors. Similar requirements exist in many sensor networks for real time control and computing applications in manufacturing industries, airplanes and ships. None of the existing MAC protocols for UWB networks can satisfy the requirements specified by the automotive industry. A thorough literature search has not found any MAC protocol to guarantee the success of message delivery with a delay limit reasonably small to the automotive industry.

Our ultimate goal in MAC design for the intra-vehicular sensor network is to find the throughput and the probability of message delivery failure as a function of the transmission power and the packet retransmissions. Given the maximum delay requirement for every sensor, we want to minimize both the transmission power and the packet retransmissions, so that the interference can be minimized and the battery life can be maximized. In this paper, we will focus on the investigation of frame delivery probability as a function of packet retransmission for both the single QoS class case and the multiple QoS class case.

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III. Problem Definition

The network under consideration consists of n sensor nodes (hereafter referred to as 'node'), equipped with only transmitters, and one (or more) sinks, which play the role of the electronic control unit (ECU), that are within one hop transmission range of all the nodes. All the nodes share a common communication channel. The nodes generate data at a constant rate of one frame every T units of time. The transmission time of each data frame is assumed to be negligible relative to T and for simplicity, is also assumed to be the same for all nodes. The nodes are classified into several QoS classes such that the minimum data delivery probability guaranteed by the class is greater than or equal to that required by the node. Since the nodes do not have a receiver module it is impossible for the nodes to sense the channel, detect collisions or receive any acknowledgements from the sink.

In this paper, we propose to allow each node to transmit x copies of the data frame at random instants within every T time units. Intuitively, a larger x implies a higher data delivery probability. However, this is true if there is only one node. In a network, typically consisting of many nodes, this greedy approach will increase the probability of collision and eventually result in a decreased data delivery probability. Therefore, the main challenge will be to determine an optimal value of x that will enable all the nodes to meet their QoS requirements.

More formally, assume that a set of n (> 1) nodes are partitioned into m QoS classes, $\{G_1, \cdots, G_m\}$, with each class containing $\{n_1, \cdots, n_m\}$ nodes. Each node in G_i requires a minimum frame delivery probability of p_i ($1 \leq i \leq m$). The core problem is to find the optimal number of transmissions x_i for each G_i, such that if every node in G_i transmits x_i times in every T units of time, it can achieve a delivery probability of at least p_i.

Based on the core problem we define the following optimization criteria:

1. Minimize the total network traffic. Alternatively, minimize x_i for every G_i. This will directly affect the energy consumption of the nodes and hence the battery life.
2. Maximize the delivery probability of the nodes in the highest priority class. In other words try to exceed the minimum required p_1 by as much as possible.

As a variant of the core problem we define another optimization problem:

3. Maximize n_1 for a given $n_2, \cdots, n_m$ and $p_1, \cdots, p_m$. In other words, maximize the number of nodes in the highest priority class given the requirements of the other classes.

One of the methods we can use (and have used) to achieve the above optimization goals is to formulate each optimization problem using NLP (Non-Linear Programming), which assumes x_i is a real number, or NLIP (Non-Linear Integer Programming), which assumes x_i is an integer. The NLP and NLIP formulations can be solved by using existing software packages (e.g. Lingo and Matlab Optimization toolbox) or a custom developed program which implements the brute force or bounded search algorithm to obtain the solutions through an exhaustive search.

IV. Single QoS Class

In this section, we examine the simple case where $m = 1$, and the optimization problem is simply to maximize the delivery probability. The following discussion presents an analytical solution to the problem in a closed form.

A. Theoretical Analysis

In this case, all the n nodes belong to the same QoS class, and each node transmits x copies of a frame at random instants in every interval T. Assuming that $t_f \ll T$, the arrival rate of the frames to the channel follows the Poisson distribution [6].

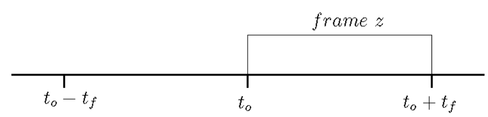


Fig. 1. Transmission of a frame at time t_0

Suppose that $node\ i$ transmits a frame at time t_0 and the duration of the transmission is t_f as shown in Fig. 1. Assuming the signal propagation delay is negligible, none of the other $n-1$ nodes should transmit during the interval $[t_0 - t_f, t_0 + t_f]$ in order that the frame does not collide. Since the packet arrival follows a Poisson process, the probability of k frames being transmitted during some time period t is given by

$$P[n' = k] = e^{-\lambda t} \frac{(\lambda t)^k}{k!} \tag{1}$$

where, $\lambda = \frac{(n-1)x}{T}$ represents the rate of background traffic generated by the other $n-1$ nodes in the interval T.

The probability that no collision occurs when $node\ i$ transmits a frame, or equivalently, the probability that the other $n-1$ nodes do not transmit any frames in $[t_0 - t_f, t_0 + t_f]$ given that $node\ i$ transmits a frame at t_0, is given by

$$D^{nc} = e^{-2\lambda t_f} \tag{2}$$

The frame delivery probability achieved by $node\ i$, $P(x)$, is defined as the probability that at least one of the x copies sent by the node during interval T is successfully received by the sink. To calculate this parameter we first find the probability, $F(x)$, that none of the transmissions were successfully received by the sink. Since the probability of collision of each transmission can be regarded as an independent event, this is given by

$$F(x) = \prod_{i=1}^{x} (1 - D^{nc}) \tag{3}$$

$$= (1 - D^{nc})^x \tag{4}$$

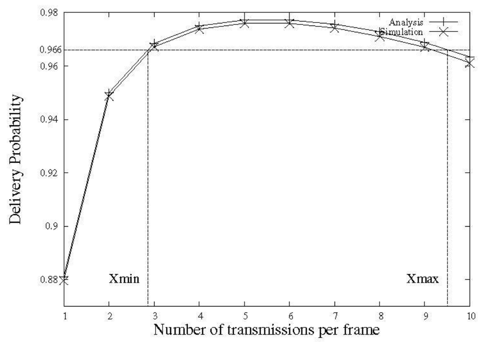


Fig. 2. Analysis and simulation results for the Single QoS class case

Then, the frame delivery probability can be calculated as

$$P(x) = 1 - F(x) \tag{5}$$

$$= 1 - (1 - e^{\frac{-2x(n-1)t_f}{T}})^x \tag{6}$$

Let $R = \frac{2t_f(n-1)}{T}$. In order to calculate the value of x at which $P(x)$ has the maximum value, we obtain the derivative $P'(x)$ which is given by

$$P'(x) = -(1 - e^{-Rx})^x[\ln(1 - e^{-Rx}) + \frac{Rxe^{-Rx}}{1 - e^{-Rx}}] \tag{7}$$

$P'(x) = 0$ has a unique solution when $x \geq 0$. This value of x is given by

$$x = \frac{\ln 2}{R} = \frac{T \ln 2}{2t_f(n-1)} \tag{8}$$

where $n > 1$.

The maximum delivery probability that can be achieved is

$$P_{max} = 1 - (1 - e^{-\ln 2})^{\frac{\ln 2}{R}} \tag{9}$$

B. Numerical Results

Fig. 2 plots $P(x)$ which is given by (6) and the simulation results where the number of nodes $n = 100$, data arrival rate $T = 1ms$ and a frame transmission time $t_f = 6.4 \times 10^{-4}ms$ (which corresponds to, for example, a transmission bandwidth of $50Mbps$ and frame size of $32bits$). The curves indicate that the delivery probability initially increases with the number of retransmissions, reaches a peak and then decreases. The simulation results shown in Fig. 2 are consistent with those from the analysis in that, the maximum value of $P(x)$ (which is about 0.977) is reached when $x = 5$ or $x = 6$ while the solution to (8) gives $x = 5.47$.

Choosing the value of x can be customized to the problem at hand. For example, let the minimum required delivery probability be $p = 0.965$. The graph indicates that this can be achieved for $3 \leq x \leq 9$. If the network traffic is to be minimized, $x = 3$ can be chosen. Alternatively we can also choose $x = 5$ to achieve maximum delivery probability. Consider another problem of node lifetime. From the graph we notice that the increase in the achieved delivery probability for $x = 5$ over $x = 3$ is small (of the order of 0.01). Accordingly, one may either choose $x = 5$ to achieve the highest delivery probability or choose $x = 3$ to reduce the number of transmissions by each node and hence improve the lifetime of the node at the expense of a slightly lower delivery probability.

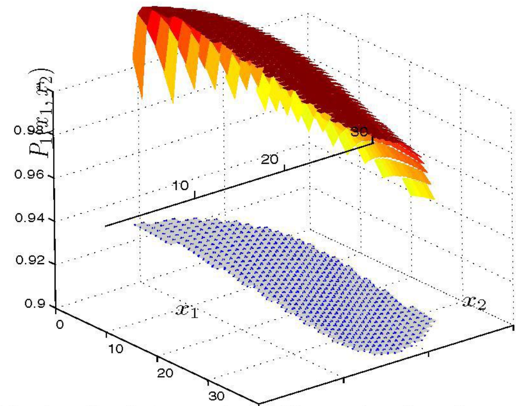


Fig. 3. Simulation results of P_1 as a function of x_1 and x_2

V. Multiple QoS Classes

A. Theoretical Analysis

In this section, we discuss the case with m (≥ 1) QoS classes $\{G_1, \cdots, G_m\}$ with corresponding delivery probability requirements $\{p_1, \cdots, p_m\}$. The number of nodes in G_i is n_i and each node in G_i transmits x_i times in every interval T. Note that the number of transmissions, x_i, is the same for all the nodes in G_i.

The probability that a transmission from a node in G_i does not collide with other transmissions can be obtained by a similar analysis as in the single QoS class case, which gives us

$$D_i^{nc} = e^{-2\lambda_i t_f} \tag{10}$$

where λ_i is the rate of background traffic generated by all the other nodes and is given by

$$\lambda_i = \frac{n_1x_1 + n_2x_2 + \cdots + n_mx_m - x_i}{T} \tag{11}$$

The frame delivery probability for each node in G_i can then be expressed as

$$P_i(x_i) = 1 - (1 - e^{-2\lambda_i t_f})^{x_i} \tag{12}$$

By the problem definition, $P_i(x_i) \geq p_i$. Then, we have

$$1 - e^{-2\lambda_i t_f} - (1 - p_i)^{\frac{1}{x_i}} \leq 0 \tag{13}$$

We can now formulate the first optimization problem, which is to minimize the total network traffic, as a non-linear programming problem (due to non-linear constraints). That is, given $n_1, \cdots, n_m$ and $p_1, \cdots, p_m$, we are required to find $x_1, \cdots, x_m$, such that

$$\min \quad \sum_{i=1}^{m} n_i \times x_i \tag{14}$$

$$\text{subject to} \quad 1 - e^{-2\lambda_i t_f} - (1-p_i)^{\frac{1}{x_i}} \le 0 \quad i = 1 \cdots m \tag{15}$$

$$1 \le x_i \le \frac{T}{t_f} \quad i = 1 \cdots m \tag{16}$$

In the objective, (14), $\sum_{i=1}^{m} n_i \times x_i$ is the total number of transmissions by all source nodes within time T. The constraint (15) guarantees that every node in $Group\ i$ $(1 \le i \le m)$ has the delivery probability of at least p_i. The constraint (16) states that the maximum number of retransmissions can not exceed $\frac{T}{t_f}$ due to hardware limitation.

The second optimization problem can be formulated similarly with the objective being that given $n_1, \cdots, n_m$ and $p_2, \cdots, p_m$, find the maximum value of $P_1(x_1)$ (and $x_1, \cdots, x_m$) subject to the constraints in (15) and (16).

For the third optimization problem the objective is that given $n_2, \cdots, n_m$ and $p_1, \cdots, p_m$, find the maximum n_1 (and $x_1, \cdots, x_m$) subject to the constraints in (15) and (16).

B. Algorithm

In this section, we describe an efficient algorithm to find the solution to the first optimization problem when there are only two QoS Classes. More specifically, consider a system consisting of two groups G_1, G_2 containing n_1, n_2 nodes and requiring a minimum delivery probability of p_1, p_2 respectively. The objective of the algorithm is to find the optimal values of x_1 and x_2 that achieves the above requirements while minimizing the total network traffic, $n_1x_1 + n_2x_2$.

The basic idea behind the algorithm proposed is to minimize the search space for the optimal solution. First, consider the whole system as a single QoS class containing $n_1 + n_2$ nodes and requiring a minimum probability of p_2 (the minimum probability required by the lowest priority class). Using the closed form expressions derived for the Single QoS Class case we can now find the minimum and maximum values of the number of transmission, x_{min} and x_{max}, that satisfy the above condition (see Fig. 2 for an illustration). Accordingly, with two QoS classes, we must have $x_{min} \le x_2 \le x_{max}$. Since $p_1 > p_2$, we need to have $x_1 \ge x_2$. This implies that $x_{min} \le x_1$. In addition, in order that the nodes in G_2 achieve a delivery probability of at least p_2 the background network traffic for a node in G_2 must be bounded by

$$n_1x_1 + (n_2-1)x_2 \le [n_1 + (n_2-1)]x_{max} \tag{17}$$

which implies that

$$x_1 \le x_{max} + \frac{n_2-1}{n_1}(x_{max} - x_2) = x'_{max} \tag{18}$$

Given the bounds on x_1 and x_2, it seems that we need to loop through all reasonable values of x_2 (i.e., from x_{min} to x_{max}, starting with x_{min}), and for each value of x_2, also loop through all reasonable values of x_1 (from x_2 to x'_{max}), until either a combination of x_1 and x_2 is found such that the minimum required p_1 and p_2 are satisfied, or the program declares that no feasible solution exists.

However, upon closer examination, we note that there is no need to loop through all possible values of x_2. Specifically, for the problem of network traffic minimization, if no appropriate x_1 can be found such that the nodes in G_1 can achieve a minimal delivery probability of p_1 when $x_2 = x_{min}$, then there does not exist any feasible solution. This is due to the fact that any increase in x_2 will not only reduce x'_{max} and thus limit the possible values of x_1, but will also increase the amount of background traffic for the nodes in G_1 and negatively affect their maximum achievable delivery probability.

Based on the above discussion, a formal description of the algorithm is presented below-

1. Find x_{min} and x_{max} such that $n_1 + n_2$ nodes can achieve a delivery probability of at least p_2 using the formula.

$$P(x) = 1 - (1 - e^{\frac{-2x(n-1)t_f}{T}})^x$$

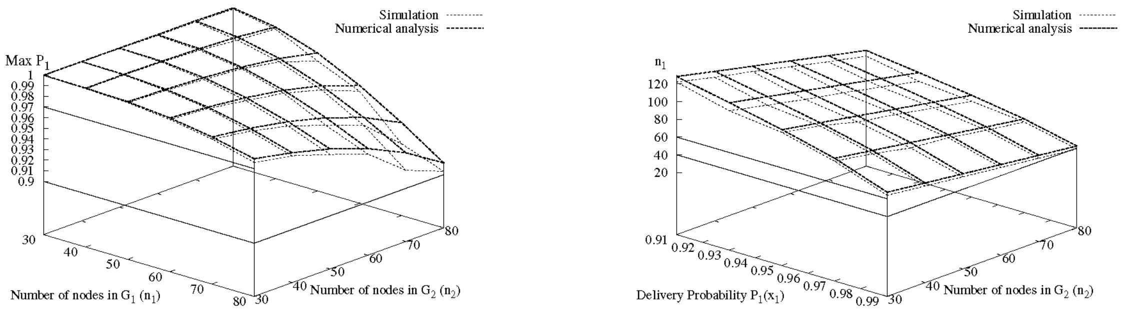
2. Set x_2 to x_{min}, Success = FALSE
3. For x_1 = x_2 to $x_{max} + \frac{n_2-1}{n_1}(x_{max} - x_2)$ in steps of 1
   $P_1(x_1) = 1 - (1 - e^{-2\frac{t_f(n_1x_1+n_2x_2)}{T}})^{x_1}$
   If $P_1(x_1) > p_1$
     Success = TRUE, exit loop
   End If
   End For
4. If Success = TRUE
   Output the values of x_1 and x_2
   Else
     No feasible solution exists
   End If
5. End

C. Numerical Analysis

To simplify the presentation of results, we assume that there are only two QoS classes. The values of T and t_f remain the same as in the single QoS class case. The required delivery probability for G_2 is set to be $p_2 = 0.9$, while n_1, n_2 and p_1 are the parameters.

Fig. 3 shows the simulation results for $P_1(x_1)$ with $p_1 = 0.95$, $n1 = 20$ and $n2 = 50$. The jagged edges of the plot for $P_1(x_1)$ are due to the facts that x_1 and x_2 can take only integer values and that only values of $P_1(x_1)$ above the required threshold of 0.95 are shown. The plot demonstrates that for a fixed value of x_2, $P_1(x_1)$ varies as in the single class case, that is, initially increasing, reaching a peak and then decreasing with x_1. For a fixed value of x_1, $P_1(x_1)$ decreases monotonically with x_2. This is due to the fact that the increased traffic from G_2 causes more collisions for frames transmitted by the nodes in G_1, hence reducing the delivery probability of the nodes in G_1.

Also, Fig. 3 shows that there exist many pairs of x_1 and x_2 satisfying the required p_1 (and p_2) and at some particular values of x_1 and x_2, the achieved $P_1(x_1)$ is greater than the required p_1 . Note that the values of x_1 and x_2 will be selected depending on the design objective. For example, the solution



(a) Max(P_1)

(b) Max(n_1)

Fig. 4. Analysis and simulation results for the multiple QoS class case

to the first optimization problem will be $x_1 = 2$ and $x_2 = 2$, which results in the least total number of transmissions.

The plots in Fig. 4 show the solutions to the optimization problems 2 and 3. Note that in the numerical analysis, x_1 and x_2 are real numbers while in simulations they are integers. This explains to a large extent the differences in the results from the numerical analysis and simulations, especially when x_1 and x_2 are large.

Fig. 4(a) shows that, when the total number of nodes is small, the achievable $P_1(x_1)$ is high for a given n_1, n_2 (and $p_2 = 0.9$). For example, when $n_2 = 30$ and $n_1 = 30$, it is possible to achieve $P_1(x_1) = 0.9997$. Note that even when n_2 has a high value ($n_2 = 80$), the achievable $P_1(x_1)$ is high (e.g. $P_1(x_1) = 0.9975$) with small value of $n_1(= 30)$. However, with large n_1 and n_2 ($e.g.\ n_1 = 80, n_2 = 80$), the achievable $P_1(x_1)$ drops to nearly 0.9. This indicates that $P_1(x_1)$ is more sensitive to the number of nodes in a higher priority group, because more transmissions are required (and thus more network traffics) to increase the delivery probability which is already high. For example, in Fig. 2, assuming the initial value of x is 1, a source node only needs two more retransmissions ($x = 3$) to increase the delivery probability by 0.088 (from 0.88 to 0.968). However, another two more retransmissions ($x = 5$) only increase the delivery probability by 0.009 (from 0.968 to 0.977).

Fig. 4(b) shows the maximum achievable n_1 when p_1 and n_2 (and p_2) are given. Assuming that $p_2 = 0.9$, when $(p_1, n_2) = (0.91, 30)$, about 120 nodes can achieve the required delivery probability of 0.91 (implying G_1 can accommodate about 120 nodes). However, when $(p_1, n_2) = (0.99, 30)$, G_1 can accommodate only about 60 nodes.

VI. Conclusion

In this paper, we have proposed a distributed MAC protocol called QoMOR that is contention based but can provide differentiated QoS (in terms of guaranteed frame delivery probabilities) without using any of the conventional ARQ or scheduling schemes. In QoMOR, each node simply retransmits each of its frames an optimal number of times within a given period to ensure its frame delivery probability is above a required threshold. Accordingly, QoMOR is useful for any network where asynchronous transmission is desired and nodes have a low throughput requirement. Since QoMOR does not require senders to receive any ACKs or NAKs, it is particularly cost-effective when UWB radios are used as UWB receiving circuits can be much more expensive than UWB transmitting circuits. Accordingly, a wireless intra-vehicular sensor (WIVES) network utilizing a combination of QoMOR and UWB is a promising alternative to the current wired network as the former can achieve better flexibility, higher data rate and lower cost [4]. However, the performance analysis of QoMOR for the single channel case shows that it cannot meet the QoS requirement that the message delivery failure probability be less than 10^{-8}. As a future work, we intend to extend the ideas presented in this paper and work on the design of a hybrid-MAC assuming that some WIVES nodes are equipped with receiving modules while others are not, and/or there are multiple DS/SS channels that the WIVES nodes can use for transmission in order to achieve the stringent QoS requirements.

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