A new multiple access scheme for DC power line communications

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Abstract

Contention detection and resolution procedure is presented. This procedure is tailored for use over the Direct Current (DC) power lines in automotive applications, but is also applicable for other multiple access networks. Bus arbitration is accomplished by each user randomly switching between carrier sense and carrier transmission modes prior to sending data. If the bus is sensed busy during this process, then the user switches to a packet reception mode. Typically, contention detection and resolution are two separate procedures. The proposed scheme effectively combines the two while maintaining controlled probability of collision. Detailed analysis of this scheme is given, revealing that the collision probability can be made arbitrarily small for the price of slightly increasing packet overhead.

Keywords

DC bus, power-line communication, multiplex, network, modem, contention, automotive, arbitration, Yamar.

I. Introduction

The car wiring (harness) is both heavy and costly. This has motivated car manufacturers to try and reduce the amount of wires in the car. The cost of "silicon", on the other hand, is constantly dropping and hence it may prove rewarding if silicon chips replace some of the car wiring. Rewarding not only in reducing price and weight, but also in increasing reliability and performance (e.g. when digital, rather than analog, signals are passed to the car speakers).

Digital communications in the automotive environment over dedicated wires is rapidly gaining momentum and recognition in practice and in the form of standardization [1][2]. An innovative, multiplexed, semiconductor module for communications over the DC battery power lines [3] can be used to transform these lines into a medium suitable for digital data transmission. Consequently, the so-called "Auto-bus" network protocols as worked out by the standardization committees of ISO and SAE, J1850 [4], CAN bus [1][2], IDB-C [5] and others, can employ the DC power line as an alternative physical layer, nicknamed *DC-bus*.

Hereinafter, we shall refer to automotive elements such as switches and controls, sensors, DC-motors and actuators, entertainment equipment etc., as *nodes*. Instead of point to point wiring, a common bus interconnects a group of automotive nodes, usually a group of nodes having common features. A node can be individually accessed by assigning to it a distinct identification tag (address) and by using a specific set of commands.

This manuscript focuses on the DC-bus arbitration procedure. Following the aforementioned network protocols, no single element is allowed to control the traffic on the DC-bus. Bus arbitration is hence accomplished by utilizing a modified *CSMA* (Carrier Sense, Multiple Access) approach properly tailored to this specific new channel and system characteristics. The arbitration procedure is described in Section III and analyzed in Section IV. Section V concludes the paper while comparing the proposed approach with some well-established MAC protocols. The general setting is described in the next section.

II. Preliminaries

We shall employ the DC power line as a medium via which various automotive nodes are interconnected. Each node is connected to the power line by means of a DC-bus modem. Thus, a DC-bus network is formed.

For each node, bus arbitration is accomplished by initiating the proposed contention detection and resolution procedure. If the bus is sensed busy during this process, then the modem switches to a packet reception mode. If no contention is detected, the modem proceeds with the transmission of the preamble field followed by the data field. A typical DC-bus packet is depicted in Figure1.

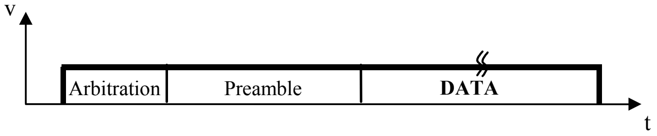

Figure 1. Typical DC-Bus message.

A critical element in achieving reliable contention resolution is the modem's carrier-sense module. This binary-output module determines whether a valid carrier signal is present on the bus. In the following we list those characteristics of the carrier-sense module combined with the system requirements that served as guiding rules in devising the arbitration procedure:

Network (topology) is configured so that the carrier-sense module detects a valid carrier signal with probability approaching one.

Arbitration duration (a single time slot) is chosen to be long enough so that when environmental noise alone is present on the bus, the probability of false alarm (mistaking noise for carrier) is practically negligible. This is detailed in Section III.A.

A modem can not sense for a carrier while transmitting and there is no alternative provisioning for detecting collisions. A collision can not readily be detected mainly due to the fact that the sender's transmission signal overpowers any incoming signals.

Collision avoidance, or actually controlled probability of collision: a transmitted packet is not acknowledged automatically and hence the arbitration procedure must be aimed at ensuring that, with sufficiently high probability, a transmission is not interfered by any other transmission and is therefore successful (as with 'conflict-free' protocols).

Research carried out by Yamar [3,6] reveal that over the battery power lines of the car, the above characteristics *a,b* are easily guaranteed for distances up to 12m and time slots of 12µSeconds. Otherwise, these characteristics are topology dependent.

Note that unlike access protocols that employ collision detection, the arbitration procedure presented herein is non-destructive in the sense that a 'winner' node need not restart the transmission of the packet (no back-off is required). The proposed algorithm is detailed in the next section.

III. Contention detection and resolution - the proposed procedure

The contention detection and resolution procedure, as executed by the modem, is comprised of the following steps described with respect to a single node.

Initialization: an n-bit register, RAR (Random Arbitration Register), is employed, whose content is randomly determined prior to each packet transmission attempt. Notably, the most and the least significant bits of this register are preset to zero for reasons that will be clarified in the sequel.

The modem waits until the bus is idle, followed by a random time-delay T_d. $0 \le T_d \le (n-1) \cdot T_b$, where T_b is the transmission time of a single-bit.

According to the bit content of the RAR, the modem switches between two operation modes:

contention detection (i.e. carrier sense-CS) mode

carrier transmission (CT) mode

(e.g., for RAR(*i*), bit position *i* of the RAR, execute CS for a period of T_b if RAR(*i*)=0, otherwise execute CT for a period of T_b.) It follows from step 1 that the first and the last modes are always CS modes. A detailed description of the two operation modes is given in sub-Section III.A.

After step 3 has been repeated n times in accordance with the bit content of the RAR, and provided that no contention (carrier) was detected during any of the CS modes, the modem proceeds with the transmission of the packet. If contention is detected, the algorithm retracts to its starting point. Recall that at least two CS modes are carried out in step 3.

It is noteworthy that the content of the RAR may be determined a-priori for each node, rather than in a random fashion, to allow for various priority handling.

A. 'Contention detection' and 'carrier transmission' modes.

CS - contention detection mode:

In order to decrease the probability of false alarm, the carrier sense module is sampled N_{cs}, equally spaced, times within a time interval T_b/m, where m is an integer in the order of 5. Contention is declared only if all N_{cs} samples indicate a valid carrier signal. Otherwise, this process is repeated for as many as m times. Once contention is detected, the modem switches to packet reception mode.

CT - carrier transmission mode:

The carrier is transmitted on the bus. (For practical reasons, such as analog-filter recovery times, the carrier transmission interval T_t satisfies $T_t \le T_b$).

In practice, N_{cs} and m will be determined empirically. It is evident from the description of the CS mode that these figures provide a compromise between the probability of false alarm, P_{FA}, and the probability of correctly detecting a valid carrier, P_{CD}. In the event of false alarm, bus access will be wrongly denied. This, however, has a minor influence on the collision probability. In the following analysis we shall assume that both P_{FA} and $1 - P_{CD}$ are sufficiently small. This assumption follows from the discussion in Section II, and has been verified by actual channel measurements.

IV. Contention detection and resolution - collision probability

As mentioned above, the modem lacks collision detection capabilities, and therefore the probability of undetected contention must be controlled according to system requirements. In the following we show that for the proposed arbitration procedure, this probability decreases to zero exponentially fast with the size of the register RAR for a given number of nodes.

A. Collision probability – The two-users case

The bus is assumed to be idle when two nodes, simultaneously, attempt to transmit a packet. Initially, each node is trying to win bus access by invoking the bus arbitration procedure. As described above, bus arbitration is accomplished by each node switching between carrier sense and carrier transmission modes according to the content of its random register, RAR.

Denote by $RAR_1(i)$ and $RAR_2(i)$, the bit in position *i* of the random register RAR of the first node and the second node, respectively. Clearly, if $RAR_1(i) = RAR_2(i)$, both nodes take the same action and the contention can not be detected. When, however, $RAR_1(i) \neq RAR_2(i)$, one node will transmit a carrier (CT mode) while the other node will sense the bus for the existence of a carrier (CS mode). In this case, contention will be detected. A typical scenario is depicted in Figure 2: two nodes access the bus simultaneously with a random time-delay difference $T_d(node2) - T_d(node1) = T_{rnd}$.

The underlying assumptions in the following analysis are: I) the preamble sequence is longer than the time consumed by Step 3 of the arbitration process, and II) all nodes are synchronized in the bit level. One can safely assume bit-level synchronization since the propagation delays are short with respect to bit length in the automotive network environment. Referring to Figure 2, the following scenarios may be encountered:

$T_{rnd} \geq T_b$: in the worst case, Node 1 will not detect the contention, and therefore proceed with the transmission of the preamble (gray area). Since the final mode of the arbitration procedure is predetermined to be CS, Node 2 will detect the preamble transmitted by Node 1 as a carrier and therefore switch to packet reception mode. Node 1 will continue its transmission undisturbed. In this scenario the contention is always resolved due to the final CS mode, hence the reason for this presetting.

$T_{rnd} < T_b$: in the worst case the contention will not be detected by any of the nodes.

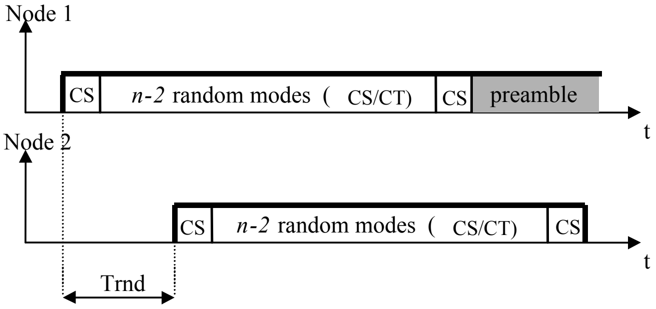

Figure 2. Bus-access timing for two nodes.

The collision probability associated with the proposed arbitration procedure can now be easily computed. Assuming that $T_d(node\,i)$ is uniformly distributed, the probability that $T_{rnd} < T_b$ is given by

$$P(Trnd < Tb) = P\left(T_d(node2) - T_d(node1) = 0\right) = \frac{1}{n^2}\cdot\binom{n}{1} = \frac{1}{n},$$

where the first equality follows from assumption II above.

The conditional probability of undetected contention (*uc*) is

$$P(uc\,/\,Trnd < Tb) =$$

$$\Pr(both\ nodes\ have\ identical\ RAR\ sequences) = \left(\tfrac{1}{2^{n-2}}\right)^2 2^{n-2} = \tfrac{1}{2^{n-2}},$$

where $n-2$ follows from the fact that the first and last bits of the RAR are predetermined.

The overall probability of undetected contention, i.e. the collision probability, for two users is given by

$$P_{uc} = \sum_{Trnd} \mathrm{P}(uc, Trnd) = P(uc\,/\,Trnd < Tb)\cdot P(Trnd < Tb) = \frac{1}{n\cdot 2^{n-2}}$$

where the second equality follows from the fact that $P(uc\,/\,Trnd > Tb)$ is negligibly small.

B. Collision probability – The multiple-users case

Now let there be k nodes connected on the DC-bus. Since there are many possible scenarios in this case, we use a different approach for summing up over all possibilities of interest.

According to Step 2 of the proposed arbitration procedure, each node randomly chooses a waiting period between zero and $(n-1)$ bit intervals. This is followed by n bit intervals in which the content of the RAR determines the mode of operation, CS or CT. In the worst case, the duration required for two contending nodes to (successfully) complete their bus arbitration phase is therefore $n + (n-1) = 2n-1$ bit intervals. (Referring to Figure 2, this occurs when the RAR of Node1 is all zero, T_{rnd} equals $n-1$ bit intervals, and the RAR of Node 2 equals $0111\ldots10$.) This is also the maximum arbitration interval required for k contending nodes. We can therefore consider each node as possessing an *equivalent register* (ER), $2n-1$ bit long, whose content is defined as follows:

Bit positions $\left[0\ldots(\frac{T_d}{T_b}-1)\right]$: random waiting period, all bits are '0' - corresponding to CS mode (we refer to these as the most significant bits, MSB);

Bit positions $\left[\frac{T_d}{T_b}\ldots(\frac{T_d}{T_b}+n-1)\right]$: equal to the content of the RAR;

Bit positions $\left[(\frac{T_d}{T_b}+n)\ldots(2n-2)\right]$: the preamble is transmitted, all bits are '1' - corresponding to CT mode (we refer to these as the least significant bits, LSB). These bits correspond to an interval $(n-1-\frac{T_d}{T_b})\cdot T_b$ long, in which the (initial fraction of the) actual preamble sequence is transmitted. Note that this interval is random due to T_d.

Let us now examine the content of two registers, corresponding to two contending nodes. Moving from MSB to LSB: the first position in which the two registers differ, will cause the node whose bit is '0' (CS mode) to switch to packet reception mode as it will sense the other node (whose bit value is '1' corresponding to CT mode). Therefore, referring to ER as holding the binary representation of a decimal value, and by some abuse of notation, it is not difficult to verify that Node 1 (with ER$_1$) will gain bus access when contending with Node 2 (with ER$_2$) if ER$_1$>ER$_2$. Thus, the following Lemma is obtained:

Lemma 1: For two users, no collision can occur if $\mathrm{ER}_1 \neq \mathrm{ER}_2$.

The following result is an immediate consequence of Lemma 1.

Lemma 2: For k users, collision will occur if there are at least two nodes with the same ER value and no other node of greater ER value.

For each node there are altogether $n \cdot 2^{n-2}$ different possible values for ER, and therefore $\left(n \cdot 2^{n-2}\right)^k$ possibilities for k nodes. Summing up over all the possibilities for collision as asserted by Lemma 2, the following collision (undetected contention) probability is obtained

$$P_{uc}(k) = \frac{1}{\left(n \cdot 2^{n-2}\right)^k} \sum_{j=0}^{(n \cdot 2^{n-2})-1} \sum_{i=0}^{k-2} \binom{k}{k-i} j^i \qquad (1)$$

As an alternative to Lemma 2, we may look at the probability that exactly one node has a greater decimal value than all the other nodes, i.e.,

$$\frac{k}{\left(n \cdot 2^{n-2}\right)^k} \sum_{j=1}^{\left(n \cdot 2^{n-2}\right)-1} j^{k-1}. \qquad (2)$$

Clearly, summing up all the terms in equations (1) and (2) must add to one. Thus, the following elegant expression for collision probability is obtained

$$P_{uc}(k) = 1 - \frac{k}{m^k} \sum_{j=1}^{m-1} j^{k-1}, \qquad (3)$$

where $m := \left(n \cdot 2^{n-2}\right)$. Since m grows exponentially fast with n, evaluating the expression in (3) quickly becomes quite involved. In the following we derive a tight upper bound on $P_{uc}(k)$ for n and k values of interest.

We shall employ the following equality for sum of powers of positive integers:

$$\sum_{j=1}^{m-1} j^{k-1} = \frac{(m-1)^k}{k} + \frac{1}{2}(m-1)^{k-1} + \sum_{i=1}^{\left\lfloor \frac{k-1}{2} \right\rfloor} (-1)^{i-1} \frac{B_i}{(2i)!}(m-1)^{k-2i} \prod_{p=1}^{2i-1}(k-p) \qquad (4)$$

where B_i are the *Bernoulli numbers* defined as $B_i = \frac{(2i)!}{2^{2i-1}\pi^{2i}} C_i$, with $C_i = 1 + \frac{1}{2^{2i}} + \frac{1}{3^{2i}} + \cdots$, and i being a positive integer. Since C_i is decreasing in i, it follows from the definition of B_i that

$$\frac{B_i}{(2i)!} = \frac{C_i}{2^{2i-1}\pi^{2i}} \qquad (5)$$

is also decreasing in i. In view of equation (3), we multiply (4) by $\frac{k}{m^k}$ and then expand the sum into a series to obtain

$$\frac{k}{m^k} \sum_{j=1}^{m-1} j^{k-1} = \left(1 - \frac{1}{m}\right)^k + \frac{k}{2m}\left(1 - \frac{1}{m}\right)^{k-1} + \left(\frac{B_1}{2!} \frac{k(k-1)(m-1)^{k-2}}{m^k} - \frac{B_2}{4!} \frac{k(k-1)(k-2)(k-3)(m-1)^{k-4}}{m^k} + \cdots \right) \qquad (6)$$

where the series (all the terms within the right-most parenthesis) terminates at $(m-1)^2$ or $(m-1)$ according as k is odd or even. Recalling that (5) is decreasing in i, and given that $m >> k$, it is easy to verify that the (absolute values of the) terms in the series decrease exponentially fast. Furthermore, since the first term in the series is positive, the sum of all the terms is non-negative. A lower bound on (6) immediately follows:

$$\frac{k}{m^k} \sum_{j=1}^{m-1} j^{k-1} > \left(1 - \frac{1}{m}\right)^k + \frac{k}{2m}\left(1 - \frac{1}{m}\right)^{k-1} \qquad (7)$$

Combining (7) and (3) we obtain the desired upper bound on the collision probability

$$P_{uc}(k) < 1 - \left(1 - \frac{1}{m}\right)^k + \frac{k}{2m}\left(1 - \frac{1}{m}\right)^{k-1} \qquad (8)$$

To see that this bound is tight we argue as follows. The series of terms in (6) is clearly bounded by the first term multiplied by the number of terms, $\left\lfloor \frac{k-1}{2} \right\rfloor$. Recalling that $B_1 = \frac{1}{6}$, it is easily seen that the outcome of this multiplication is negligibly small compared to the expression on the right-hand side of (7). The bound in (8) is plotted in Figure 3 for $k = 32, 128$ nodes as a function of the arbitration parameter n.

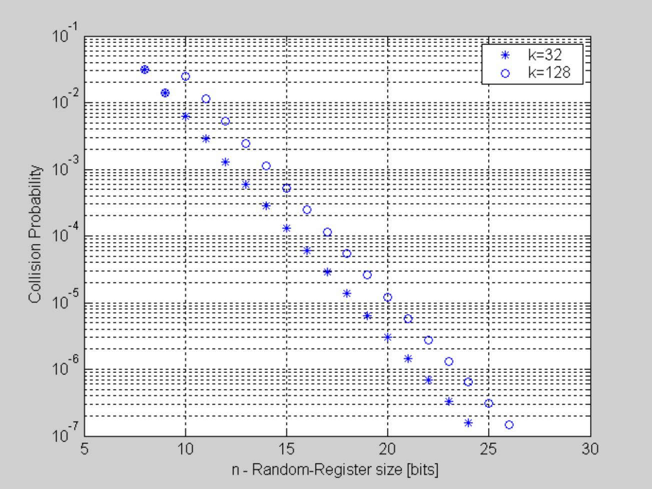

Figure 3. Collision probability as a function of the arbitration parameter n.

In Figure 4 we plotted the collision probability as a function of the number of nodes, k, for $n = 16, 20$. In this case, increasing n by only 4 bits improves the performance of the proposed arbitration procedure by one order of magnitude.

Finally we notice here that the number of instantaneous contending nodes is typically much smaller than the total number of connected nodes, denoted by M .

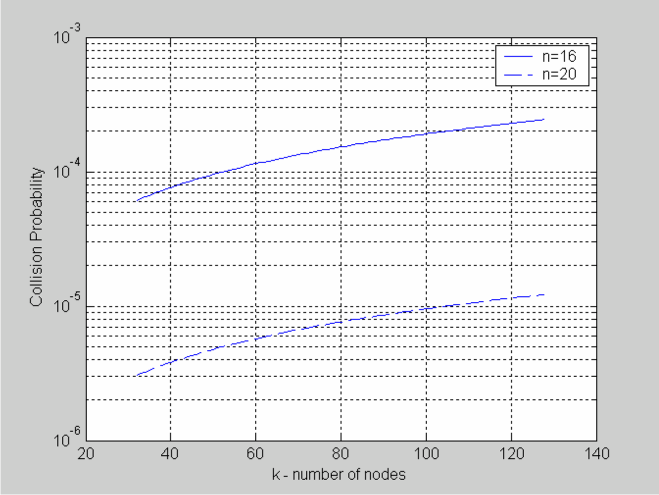

Figure 4. Collision probability as a function of the number of nodes**.**

The number of contending nodes, K , is clearly a random variable, whose sample space is $k \in \{2,3,\ldots,M\}$, with some discrete probability density function $f(k)$. Then the expected value of $P_{uc}(k)$, defined as

$$\overline{P}_{uc} = E\left(P_{uc}(k)\right) = \sum_{k=2}^{M} P_{uc}(k) f(k) \qquad (9)$$

is the average collision probability. By combining (8) and (9) a tight upper bound on $\overline{P}_{uc}$ is obtained

$$\overline{P}_{uc} < \sum_{k=2}^{M} \left[1 - \left(1 - \frac{1}{m}\right)^{k} + \frac{k}{2m}\left(1 - \frac{1}{m}\right)^{k-1} \right] f(k) \, . \qquad (10)$$

V. Conclusions

An arbitration procedure for detecting and resolving contention on a multiple access bus has been presented and analyzed. It is easy to implement and requires no collision detection mechanism. Since collision probability can be made arbitrarily small, the proposed procedure may be characterized as 'conflict-free', yet no predetermined channel allocation is required (as with e.g. TDMA, FDMA). At the same time, it can be classified as a CSMA protocol with contention detection, but without collision detection.

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