Detecting Approaching Sources in Infrastructure-Less Vehicular Communications by a Simple Signal Processing Method

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Abstract— This work presents a new low-cost test to detect approaching sources, for possible application to inter-vehicular communications. We focus on infrastructure-less vehicular communications, where GPS and other distance vector-based networks are not employed. In fact, here we only need a cheap radio transmitter/receiver. In the proposed testing procedure, the only signs of the difference between the envelope samples of the received signal are used. The testing variable is obtained under the constant false alarm rate criterion, according to the binomial statistical distribution. The performance of the test in terms of probability of detection is evaluated versus SNR, speed, and distance between transmitter and receiver. We have evidenced the effectiveness of our solution, being independent of both the motion and propagation models.

Index Terms— Inter-vehicular communications, hypothesis testing, performance analysis, detection algorithms.

I. Introduction

In the last years, testing for statistical distribution has received an ever increasing attention, especially in the application fields of both signal processing for communications [1]-[2] and wireless communications [3]. These methods are often interested in solving some sort of detection problem by evaluating a testing variable (that is a function of the observed data) to compare to a pre-computed threshold [4]. The problem is usually formulated as a conventional binary hypothesis test, where the two hypotheses H_0 and H_1 correspond, respectively, to the absence or presence of the signal of interest. Some one-dimensional testing variables are used to minimize the time needed before a correct detection is declared, limiting the computational costs of the decision device [5]. The Constant False Alarm Rate (CFAR) procedure is typically used to perform effective tests [6]. The CFAR algorithm is realized in two steps: first, the threshold of the test is evaluated, for a fixed value of the false alarm probability; then, the testing variable is compared with the previously determined threshold. The performance of the test is evaluated in terms of the detection probability (i.e. the power of the test) as the relative frequency of occurrence of overcoming that threshold.

In our work, we are interested in presenting a new test, namely the binomial test, to detect approaching sources for possible application to wireless vehicular communications. In particular, we apply our test to inter-vehicular communications as a *proof of concept* of the method here introduced, considering infrastructure-less vehicular communications. Conversely, if we could employ a fully organized vehicular sensor network (VSN) equipped with GPS and distance vector systems (e.g. magnetic sensors or laser range finders), other efficient methods can be applied, such as the ones depicted in [7]-[8], at the cost of dramatically raising the computational complexity of the devices. In the last years, there has been an increasing interest in vehicular communication technologies and VSNs [9]. Such systems can exploit both the advantages of vehicular ad hoc networks (VANETs) and wireless sensor networks (WSNs), thus leading to many applications, such as the one related with traffic safety [7] and vehicle security [10]. In particular, VSNs are realized by many sensor nodes deployed on roads or vehicles, cooperating through vehicle-to-vehicle (V2V), vehicle-to-roadside (V2R), and vehicle-to-infrastructure (V2I) communications. There is a lot of works in this fields, focusing in particular on preventing rear-end collisions among vehicles by V2V communications. The authors in [11]-[12] rely on roadside infrastructures to achieve this goal, but this is sometimes not feasible in suburban and rural areas. Conversely, the work in [7] deals with frontal collisions due to improper overtaking, while [13] presents an intelligent V2V broadcast with implicit acknowledgment for highway safety. Reference [14] also uses V2V communications to avoid rear-end collisions on highways. However, all these proposed schemes rely on intelligent and high costly infrastructure roadside units.

Here, we focus on low-cost inter-vehicular communications (i.e. inter-vehicular communications characterized by an infrastructure-less framework) where our test can be effectively applied, minimizing the cost and the computational complexity of the devices. What we need is a cheap radio transmitter/receiver to efficiently deploy our testing method. In our testing method, the only signs of the difference between the

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envelope samples of the received signal are used. The testing variable is obtained under the constant false alarm rate criterion, according to the binomial statistical distribution.

The remainder of this work is organized as follows. Section II introduces the new binomial test for infrastructure-less vehicular communications, while the performance of test is investigated in Section III. Some numerical results are outlined in Section IV and finally, our conclusions are depicted in Section V.

II. Test for Inter-Vehicular Communications

A. System Model

Let now $s(t)$ be the received useful signal (if present) which is assumed to be affected by additive white Gaussian noise $w(t)$, with zero-mean and variance σ_W^2. The received signal is $r(t)=s(t)+w(t)$ under the H_1 hypothesis, and $r(t) = w(t)$ otherwise. For the sake of compactness, all the signals are expressed in terms of their representative vectors. The signal $r(t)$, represented by the vector $\mathbf{r} = \mathbf{s} + \mathbf{w}$, is sampled at the receiver side with a sampling period T_s. Now, the sequences (made of N samples) of the received signal, of the useful signal, and of the noise are defined as, respectively:

$$\begin{aligned} \mathbf{r} &= [r_1, r_2, r_3 ... r_N]^T \\ \mathbf{s} &= [s_1, s_2, s_3 ... s_N]^T \\ \mathbf{w} &= [w_1, w_2, w_3 ... w_N]^T \end{aligned} \quad . \tag{1}$$

B. Binomial Testing for Approaching Sources

Let us now introduce the test to detect approaching sources for application to inter-vehicular communications. In particular, let us consider the series $\mathbf{E} = |\mathbf{r}|$ composed by N samples of the envelope magnitude (i.e. the square root of the power) of the received signal:

$$\mathbf{E} = [E_1, E_2, ..., E_N]^T . \tag{2}$$

It has to be noted that the signal level may be very week at signal samples. To overcome this problem we need an integration operation that is realized as follows, by means of an averaging procedure. Let us define the series $\mathbf{Q} = [Q_1, Q_2, \ldots, Q_M]^T$, composed by M variables, and obtained from (2) by averaging $N_A = N / (2\,M)$ samples of the envelope magnitude as follows:

$$\begin{aligned} Q_1 &= \sum_{i=1}^{N_A} E_i - \sum_{i=N_A+1}^{2\cdot N_A} E_i \\ Q_2 &= \sum_{i=2\cdot N_A}^{3\cdot N_A} E_i - \sum_{i=3\cdot N_A+1}^{4\cdot N_A} E_i \\ &\ldots \\ Q_M &= \sum_{i=N-2N_A+1}^{N-N_A} E_i - \sum_{i=N-N_A+1}^{N} E_i \end{aligned} \quad . \tag{3}$$

However, we are going to discuss, in Section IV.A, that the above series has very poor performance to evidence the power differences due to motion. Alternatively, we can improve the robustness of the random series by interlacing (by the factor M) the averaged samples of the envelope magnitude as follows:

$$\begin{aligned} Q_1 &= \sum_{i=1}^{N_A} E_{M\cdot i-M+1} - \sum_{i=N_A+1}^{2\cdot N_A} E_{M\cdot i-M+1} \\ Q_2 &= \sum_{i=1}^{N_A} E_{M\cdot i-M+2} - \sum_{i=N_A+1}^{2\cdot N_A} E_{M\cdot i-M+2} \\ &\ldots \\ Q_M &= \sum_{i=1}^{N_A} E_{M\cdot i} - \sum_{i=N_A+1}^{2\cdot N_A} E_{M\cdot i} \end{aligned} \quad . \tag{4}$$

Now, we define the binomial test to discriminate between the two hypotheses:

H_0: the source is still or characterized by a chaotic motion;

H_1: the source is approaching the receiver or, equivalently, the receiver is moving towards the source.

In terms of received power (and, equivalently, in terms of the envelope magnitude), at the receiver side, the above hypotheses result in:

H_0: the received envelope magnitude does not increase;

H_1: the received envelope magnitude increases.

At this point, we evaluate the sign of the variables $\{Q_i\}$, defined in (3) or (4) alternatively, as follows:

$$\begin{aligned} B_1 &= sgn(Q_1) \\ B_2 &= sgn(Q_2) \\ &\ldots \\ B_M &= sgn(Q_M) \end{aligned} \quad , \tag{5}$$

where $sgn(\cdot)$ accounts for the signum function. Then, we compute how many times the variables $\{B_i\}$ are less than zero (i.e. number of successes) out of a sequence of M observations. The number of success, namely k, is close to $M/2$, under the H_0 hypothesis. Therefore, we declare that the test is passed if k is greater or equal to a proper threshold value T, with $M/2 < T < M$:

$$\begin{aligned} H_0 &: \quad k < T \\ H_1 &: \quad k \geq T \end{aligned} \quad . \tag{6}$$

It has to be underlined that our test is able to operate regardless the adopted motion model. In fact, the method does not test the amplitude of the received power but only the signs of the received power differences, being also very robust and independent of the wireless propagation model.

III. Performance Analysis

A. The Binomial Distribution

In probability theory and statistics, the binomial distribution is the discrete probability distribution of the number of successes in a sequence of M independent yes/no experiments, each of which yields success with probability p. Such a success/failure experiment is also called a Bernoulli experiment or Bernoulli trial; when

M=1, the binomial distribution is a Bernoulli distribution [15]. In general, if the random variable K follows the binomial distribution with parameters M (i.e. the size of the test) and p (i.e. the probability of successes), we write $K \sim B(M, p)$. The probability of getting exactly k successes in M trials is given by the probability mass function, defined as follows:

$$f(k;M,p) = Pr(K=k) = \binom{M}{k} p^k (1-p)^{M-k}, \quad (7)$$

for k = 0, 1, 2, ..., M, and where:

$$\binom{M}{k} = \frac{M!}{k!(M-k)!} = C(M,k), \quad (8)$$

is the binomial coefficient. Eq. (7) means that we want k successes (p^k) and $M - k$ failures $(1-p)^{M-k}$. However, the k successes can occur anywhere among the M trials, and there are $C(M, k)$ different ways of distributing k successes in a sequence of M trials. In creating reference tables for binomial distribution probability, usually the table is filled in up to $M/2$ values. This is because for $k>M/2$, the probability can be calculated by its complement as:

$$f(k;M,p) = f(M-k;M,1-p). \quad (9)$$

Then, the cumulative distribution function (CDF) can be expressed as:

$$CDF(k;M,p) = Pr(K \le k) = \sum_{i=0}^{\lfloor k \rfloor} \binom{M}{i} \cdot p^i \cdot (1-p)^{M-i}, \quad (10)$$

where $\lfloor k \rfloor$ is the greatest integer less than or equal to k. The CDF in (10) can also be represented in terms of the regularized incomplete beta function as follows:

$$\begin{aligned} CDF(k;M,p) &= Pr(K \le k) = I_{1-p}(M-k,k+1) \\ &= (M-k)\binom{M}{k}\int_0^{1-p} t^{M-k-1}(1-t)^k\, dt \end{aligned}. \quad (11)$$

B. Hypothesis H_0

The M random variables expressed by (5) can be modeled as M zero-mean independent and identically distributed (i.i.d.) Bernoulli random variables, with parameters $p = q = 0.5$, following the binomial distribution. Let us note that the M random variables in (3) and (4) have the same statistical distribution, since they only depend on the same number of averages of the noise (assumed to be stationary) at the receiver's input.

The threshold T is chosen so that the corresponding probability of false alarm (P_{FA}) is equal to the desired one (and obtained by the CFAR procedure). The probability of getting exactly k successes out of M observations is given by the probability mass function in (7), where now $p = q = 0.5$ in the null-hypothesis. Then, since we are interested in evaluating the probability of exceeding the threshold T, we need to consider the complement of the CDF expressed by (11) with $k = T$ and defined as follows:

$$Pr(K > T) = 1 - CDF(T;M,p). \quad (12)$$

Then, the value of the threshold T is determined, by the CFAR procedure in the H_0 hypothesis, as the value by which the following is true:

$$\begin{aligned} CDF(k;M,p) &= I_{1-p}(M-T,T+1) \\ &= 1-P_{FA} \end{aligned}, \quad (13)$$

assuming $p = q = 0.5$.

Fig. 1 shows the binomial CDF obtained by means of M=100 testing variables is shown, along with the two straight lines corresponding to the percentile 0.99 (i.e. 1-P_{FA}, with $P_{FA} = 10^{-3}$) and to the percentile 0.99999 (i.e. 1-P_{FA}, with $P_{FA}=10^{-5}$), respectively. It is now easy to see how the number of testing variables directly impacts on the threshold. Many testing variables allow a finer threshold setting corresponding to the P_{FA} targets (according to the CFAR procedure), while few testing variables result in a roughly threshold setting with an actual P_{FA} not according to the CFAR procedure.

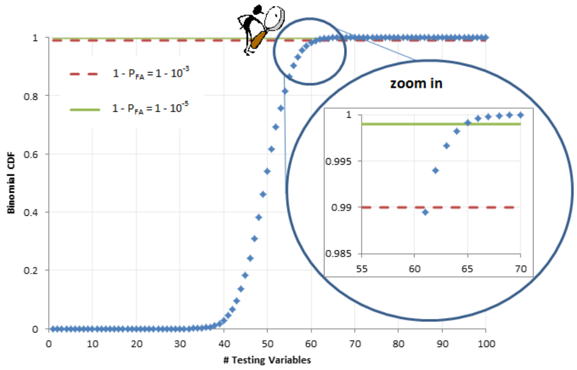

Figure 1. Binomial CDF obtained by means of M = 100 testing variables, and the percentile 0.99 (i.e. 1- P_{FA}, with $P_{FA} = 10^{-3}$) and 0.99999 (i.e. 1- P_{FA}, with $P_{FA}=10^{-5}$).column.

C. Hypothesis H_1

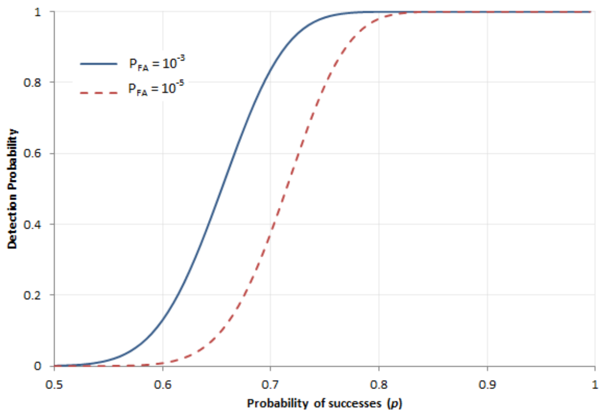

Figure 2. Probability of detection versus the successes probability p, for two different values of the false alarm probability.

In this case, the source is approaching the receiver (or, equivalently, the receiver is moving towards the source).

The received power increases, and the M random variables (now with expected value less than zero) expressed by (5) can be modeled as M i.i.d. Bernoulli random variables, following binomial statistics, with $p>q$. Then, the test is accomplished under the H_1 hypothesis to evaluate the detection probability P_D, for different p, with the constraint that $p > q$. Of course, if the source is closer and closer, p becomes greater and greater than q. Fig. 2 shows the probability of detection versus the successes probability p, for two different values of the false alarm probability (i.e. $P_{FA}=10^{-3}$ and $P_{FA}=10^{-5}$).

In practice, the parameter p depends on both physical and geometrical operating conditions. In fact, the parameter p accounts for the distance between transmitter and receiver as well as the SNR values. The way how the parameter p, the SNR values, and the distance d between source and receiver are related each other depends on both the kind of motion (e.g. speed) of that source and on the fading model assumed for the wireless channel, as shown in the next Section.

IV. Results

A. Numerical Models of Motion and Propagation

As said in Section II.B, our test is suitable for any choice of both the motion and fading models: in fact, from one model to another, only the specific mathematical relations between the distance d, the parameter p and the SNR values change, while our test still remains valid (i.e. the output of the test are now characterized by different scale factors, depending on the adopted model). The effectiveness of the binomial test relies on the fact that the method does not test the amplitude of the received power tests but only the signs of the received power differences, being very robust and independent of the wireless propagation model since it must detect only the slope sign of the received power.

As a proof of concept of the method here proposed, let us assume a wireless channel model where the power loss of the received signal is proportional to the inverse square of the distance (free space model) as follows [16]:

$$P(d) = \frac{P_0}{d^2}, \tag{14}$$

where P_0 is the power for $d = 1$ m. The noiseless component of the envelope magnitude[1] of the received signal, say $\bar{E}$, varies as the inverse of the distance:

$$\bar{E}(d) = \frac{\sqrt{P_0}}{d}. \tag{15}$$

Then, assuming a noise variance $\sigma_w^2 = 1$ for any distance d, the SNR can be expressed as:

$$SNR(d) = \frac{\left[\bar{E}(d)\right]^2}{\sigma_w^2} = \left[\bar{E}(d)\right]^2, \tag{16}$$

and considering a SNR = 20 dB for a distance d=100 m, (15) re-writes as follows:

$$\bar{E}(d) = \frac{1000}{d}. \tag{17}$$

Now, if the times of the observations are small (i.e. the speed can be assumed constant for a very small time interval), we can assume that the motion of the source can be described by the following equation versus the time t:

$$d = d_1 - v\cdot t + a\cdot t^2 + \cdots, \tag{18}$$

where d_1 is the initial coordinate for t = 0, and v is the relative speed between the source and the receiver. Now, by means of the Taylor expansion up to the first order under the assumptions of small displacements we can re-write (18) as follows:

$$\bar{E}(d_2) = \frac{\bar{E}(d_1)\cdot d_1}{d_1 - v\cdot t + a\cdot t^2 + \cdots} \approx \bar{E}(d_1)\cdot(1+\frac{v\cdot t}{d_1}), \tag{19}$$

obtaining the same equation of a simple uniform linear motion in the radial direction. As a consequence, we can write the following relation for each of the M random variables Q (being $\bar{Q}$ the noiseless component of Q):

$$\bar{Q}(d) = \frac{\bar{E}(d)\cdot v\cdot t}{d}, \tag{20}$$

We note that $\bar{Q}(d)$ is directly proportional to the time period t, but the value of t strongly differs in the case represented by (3) or (4). In addition, from (20), we see that a large t allows Q (and $\bar{Q}$) to better evidence the power differences due to motion. Hence, as mentioned in Section II.B, it is preferable to evaluate Q by means of (4), instead of (3), obtaining a large t.

Then, according to the previous discussion in Section III.B, at a first glance one could think that the best choice is to adopt M, i.e. the number of testing variables, as large as possible (so that the threshold is effectively evaluated). Unfortunately, this corresponds to a low number of averages, N_A, resulting in low detection probabilities in the H_1 hypothesis. Hence, the number of testing variables must be chosen as a reasonable trade-off between these two afore-mentioned requirements. It is now possible to evaluate the detection probability corresponding to any d, v and t.

B. Numerical Results

For our numerical trials, we have considered a band-pass useful signal with 22 MHz of bandwidth, corrupted by additive white Gaussian noise (AWGN) with several SNR. The bandwidth of the complex envelope is 11 MHz, then the sampling frequency can be chosen, according to

[1] For the sake of the simplicity, we omit the subscript from $\bar{E}(d)$ and $\bar{Q}(d)$.

the Nyquist theorem, (at least) equal to 22 MHz. Assuming an observation timing window t = 0.1 seconds, we have 2.2 10^6 samples of the complex envelope of the received noisy signal. In the following, we have decided to work with 100 testing variables (i.e. 100 samples of the series **Q**), since this value represents a reasonable trade-off between test performance and accuracy. In particular, we have evaluated the performance of our test for two different P_{FA} (i.e. P_{FA}=10^{-3} and P_{FA}=10^{-5}), varying some parameters of interests (i.e. SNR, speed and distance). Fig. 3 and Fig. 4 report the detection probabilities versus different speed (expressed in Km/h) for two cases of interest. In Fig. 3, the relative distance between transmitter the receiver is d = 500 m (and SNR = 6 dB), while Fig. 4 illustrate the case of d = 100 m (and SNR = 20 dB), respectively. It is interesting to note that, in both cases, higher detection probabilities are obtained with higher speed, confirming the efficiency of our method to allow a fast detection of approaching sources.

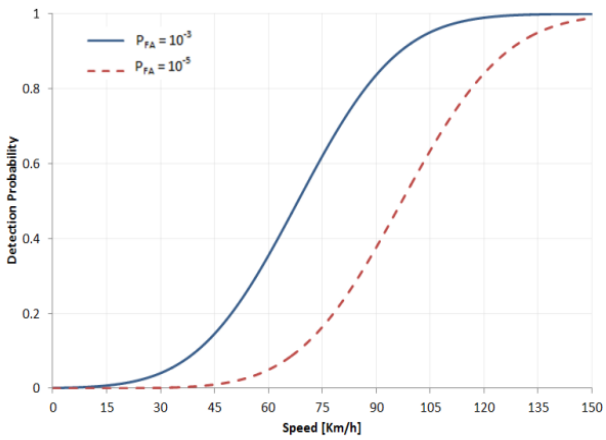

Figure 3. Detection probability versus relative speed (expressed in Km/h) for the case of d = 500 m (i.e. SNR = 6 dB), and two PFA of interest.

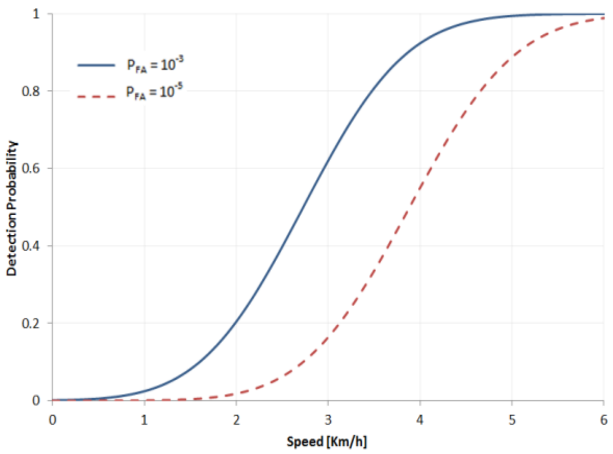

Figure 4. Detection probability versus relative speed (expressed in Km/h) for the case of d = 100 m (i.e. SNR = 20 dB), and two PFA of interest.

In practice, we are able to provide an early alarm for possible vehicle crash avoiding near-end collisions with an inter-vehicle distance of 500 m and minimum relative speed of 100 Km/h (as shown in Fig. 3), and with a lower minimum speed (5 Km/h) for closer distances (see Fig. 4).

Finally, Fig. 5 and Fig. 6 illustrate the detection probabilities of our test versus different distances and different SNR values, respectively, in case of relative speed of 3.6 and 36 Km/h, respectively. In particular, Fig. 5 shows that our method is really effective for application to vehicular communications. In fact, the algorithm allows detecting an approaching source faster at higher speeds. If the relative speed is equal to 3.6 Km/h, the algorithm can detect an approaching source only when the relative distance is less than 150 meters, while the method can detect the transmitter at higher distances (less than 350 meters) if the relative speed is higher, i.e. 36 Km/h.

In conclusion, our test is characterized by higher detection probabilities in correspondence of small distances (< 100 m) or, equivalently, for high SNR values (i.e. when the source is really approaching the receiver and the collision must be avoided).

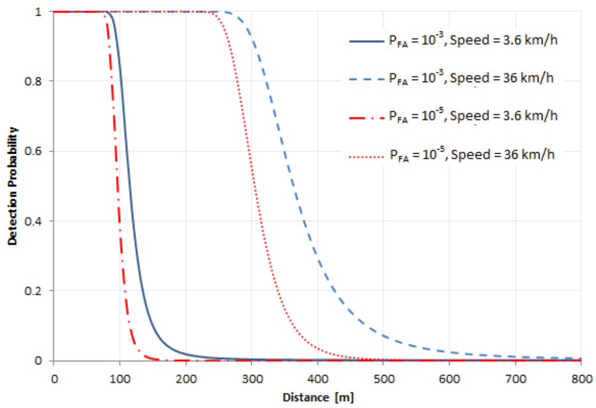

Figure 5. Detection probability of the binomial test versus distance in the case of a relative speed of 3.6 and 36 Km/h and two P_{FA} of interest.

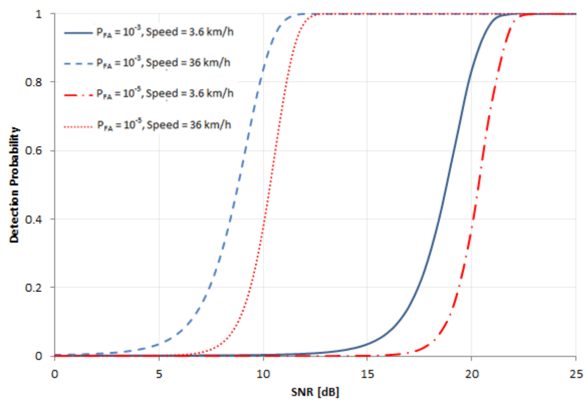

Figure 6. Detection probability of the binomial test versus SNR in the case of a relative speed of 3.6 and 36 Km/h and two P_{FA} of interest.

V. CONCLUSION

A new test for detecting approaching sources has here introduced for application to inter-vehicular sensing. The test has been designed as simple as possible in order to be independent from both the motion and channel propagation models. We have obtained a binomial test that can be correctly employed in many different operating scenarios (i.e. rural and urban environment). The obtained outcomes evidence the efficiency of the proposed solution, for application to low-cost inter-vehicular communications.

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