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# Hybrid TOA/RSS and TDOA/RSS Location Estimation Schemes for Short-Range Wireless Networks

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***Index Terms*** **– Location estimation, TOA, RSS, TDOA, short-range networks**

## INTRODUCTION

The dominant location estimation techniques used in Wireless Cellular Networks (WCN) include time of arrival (TOA) and time difference of arrival (TDOA) [1]. Although Received Signal Strength (RSS) measurements are easily available [2], the RSS-based location estimation has been circumvented in WCN. The reason lies in its dependency on the distance of the located device to the reference points (i.e. base stations); namely: the farther the located device is from the BS, the lower the accuracy. In short-range networks, the distances between the devices and the reference points are typically by an order of magnitude smaller than in WCN. For example, the transmission range of WiFi, UWB and WSN is around 30 meters; for Bluetooth, it is 10m. At this range, the performance of the RSS-based location estimation is improved. Moreover, since short-range networks are characterized by high device density, the likelihood of a located device being in very close proximity of a reference point is substantial. Hence, exploiting RSS in short-range networks could provide low-cost improvement in the location accuracy.

In this paper, hybrid location estimation techniques, based on the combination of RSS measurements and either TOA or TDOA measurements, are studied. The objective is to improve the accuracy of the location estimation in short-range networks by taking advantage of easily available RSS measurements. Indeed, the results indicate that hybrid schemes improve overall location estimation accuracy and significantly improve the behavior in the proximity of the reference devices with respect to TOA-only and TDOA-only schemes.

In [3], the authors established the feasibility criteria for location estimation in wireless networks, in terms of the relationship between the number of reference devices and the number of devices whose location is being determined (blindfolded devices). They also computed the Cramer-Rao Bounds (CRB)[1] for TOA-based and RSS-based estimation for arbitrary number of reference points and located devices. They did not consider the case of location estimation based on the combination of different location techniques. Here, these results are extended to the case of the TOA/RSS and TDOA/RSS hybrid schemes.

## THE CRB OF TOA/RSS AND TDOA/RSS LOCATION ESTIMATION SCHEMES

Consider a wireless device whose location is being estimated, denoted as D-0, and a set of reference points, $N$, which are within the range of D-0. Subsets of reference points capable of performing TOA and RSS measurements are denoted as $N_{TOA}$ and $N_{RSS}$, respectively. A reference point can be in either of the two subsets, as well as in both, i.e. $N = N_{TOA} \cup N_{RSS}$.

[1] CRB is the statistical term for the lowest achievable mean square error

Assume that the actual location coordinate of D-0 is $\theta_0 = [x_0, y_0]$. The location estimation problem then consists in finding the estimate of the coordinate, $\hat{\theta}_0$, given the coordinate vector of the reference points $\theta = [\theta_1,\ldots,\theta_{card(N)}]$, where $card(N)$ denotes the cardinal number of $N$.

### *The CRB of TOA/RSS scheme*

The TOA observations are commonly modeled as normal random variables $\sim N(d_{i,0}/c, \sigma_T^2)$, where $d_{i,0}$ is the separation of D-0 and reference point $i$, $c$ is the speed of radio-wave propagation and $\sigma_T$ is the parameter describing the joint nuisance of the multipath nature of the propagation channel and the measurement error. The RSS measurements are log-normal random variables $\sim N(P_0(dB), \sigma_{sh}^2)$, with $P_0(dB) = P_t(dB) - 10n_p\log_{10}(d_{0,i})$, where $P_0(dB)$ and $P_t(dB)$ are the decibel values of the mean received power and the mean transmitted power of D-0 respectively, $n_p$ is the propagation exponent, and $\sigma_{sh}^2$ is the variance of the lognormal shadowing.

The CRB, i.e. the minimum achievable mean square error of any estimator $\hat{\theta}_0$ is:

$$\sigma_{CRB}^2 = \min_{\hat{\theta}_0} E[(\hat{x}_0 - x_0)^2 + (\hat{y}_0 - y_0)^2]$$

Using the tools of statistical inference [4], the CRB can be derived from the known statistical properties of the TOA and RSS measurements. The expression for the CRB on the variance of the TOA/RSS location estimation scheme was derived in [5]:

$$\sigma_{CRB}^2 = \frac{\dfrac{card(N_{TOA})}{c^2\sigma_T^2} + b\sum_{i\in N_{RSS}} d_{i,0}^{-2}}{\dfrac{1}{(c^2\sigma_T^2)^2}\sum_{i\in N_{TOA}}\sum_{\substack{j\in N_{TOA}\\ i<j}} A_{i,j}^2 + \dfrac{b}{c^2\sigma_T^2}\sum_{i\in N_{TOA}}\sum_{j\in N_{RSS}}\dfrac{A_{i,j}^2}{d_{j,0}^2} + b^2\sum_{i\in N_{RSS}}\sum_{\substack{j\in N_{RSS}\\ i<j}}\left(\dfrac{A_{i,j}}{d_{i,0}d_{j,0}}\right)^2} \tag{1}$$

where $b = \left(\dfrac{10n_p}{\sigma_{sh}\log 10}\right)^2$, $A_{i,j} = \dfrac{d_{0\times i,j}d_{i,j}}{d_{i,0}d_{j,0}}$ is a unitless parameter, representing the *geometric conditioning* [3] of devices $i$ and $j$ with respect to D-0, and $d_{0xi,j}$ is the length of the shortest distance between D-0 and the line connecting $i$ and $j$. The $A_{i,j}$ in fact represents the area of the parallelogram defined by the devices D-0, $i$ and $j$, normalized by $d_{i,0}\cdot d_{j,0}$. The concept of geometric conditioning is illustrated in Figure 1.

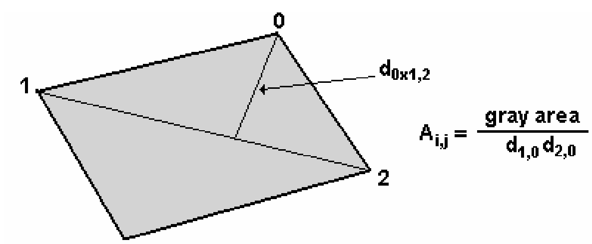


**FIGURE 1** GEOMETRIC CONDITIONING OF DEVICES 1 AND 2 WITH RESPECT TO DEVICE 0.

It is worth to analyze the expression (1). The first term in the denominator represents the contribution of the TOA measurements to the CRB. It depends only on the number of reference devices and their geometric conditioning with respect to D-0, regardless of their separation. The third term in the denominator represents the contribution of the RSS observations. Due to $(d_{i,0}\cdot d_{j,0})^2$ in the denominator of this term, the contribution of the RSS measurements to the location accuracy is determined by the separation of D-0 from the reference points, as expected. Reducing this separation (e.g, by increasing the node density) increases the RSS contribution. The above remarks about the terms in the denominator are also valid for the first and the second terms in the numerator, respectively. Therefore, the analysis of the expression (1) confirms the following two statements:

- the accuracy of TOA-based location estimation depends on the number of reference points and their mutual positioning, but does not depend on the distance between the located device and the reference points;
- the accuracy of the RSS-based estimation is greatly dependent on both the number of the reference devices and the distance between the located device and the reference points.

The ability to perform TOA observations implies full network synchronization. Therefore, the TOA/RSS scheme is applicable to synchronized short-range networks only. This requirement is very stringent, and can be relaxed by using TDOA/RSS scheme, discussed in the following section.

### *The CRB of the TDOA/RSS location estimation scheme*

The lack of synchronization in short-range networks is a major obstacle for the use of location estimation techniques based on the TOA, where transmitters and receivers need to have synchronized clocks and bi-directional communication. Global synchronization is a serious challenge in short-range networks, due to the requirements related to highly precise central clock in wireless devices and low-network installation cost. In addition, even if the synchronization is achieved, at least three synchronized stations must be observed within the radio coverage of the located device for trilateration. Due to short ranges, this drastically increases the required number of synchronized devices in the network.

The lack of synchronization can be mitigated by replacing TOA measurements with TDOA. One TDOA observation is the difference between TOA observations of two reference points, which allows elimination of the unknown offset between the clocks. Usually, one of the reference points used to obtain the difference between TOA observations is fixed, and can be assigned index 1. TDOA observations can than be modeled as normal random variables $\sim N((d_{i,0}-d_{1,0})/c, 2\sigma_T^2)$. Note that reference point with index 1 cannot provide independent observation, hence $card(N_{TDOA}) = card(N_{TOA}) - 1$. Therefore, in order to cope with the lack of synchronization, the TDOA sacrifices one observation and doubles the variance of the remaining $card(N_{TOA}) - 1$ observations.

The computation of the CRB of the TDOA/RSS was done in [6], and the closed-form expression is:

$$\sigma_{CRB}^2 = \frac{\dfrac{card(N_{TDOA})}{c^2\sigma_T^2} - \dfrac{1}{2c^2\sigma_T^2}\sum_{i\in N_{TDOA}}\cos\gamma_{1,j} + b\sum_{i\in N_{RSS}} d_{i,0}^{-2}}{\dfrac{1}{(2c^2\sigma_T^2)^2}\sum_{i\in N_{TDOA}}\sum_{\substack{j\in N_{TDOA}\\ i<j}}(A_{1,i}+A_{1,j}-A_{i,j})^2 + \dfrac{b}{c^2\sigma_T^2}\sum_{i\in N_{TDOA}}\left[\begin{array}{l} A_{i,j}^2(d_{1,0}^{-2}+d_{i,0}^{-2}) + \\ \displaystyle\sum_{j\in N_{RSS}}\left(\frac{A_{1,j}-A_{i,j}}{d_{i,0}}\right)^2\end{array}\right] + b^2\sum_{i\in N_{RSS}}\sum_{\substack{j\in N_{RSS}\\ i<j}}\left(\frac{A_{i,j}}{d_{i,0}d_{j,0}}\right)^2} \quad (2)$$

where $\gamma_{1,i}$ is the angle between $d_{0,1}$ and $d_{0,i}$. The comments made on the expression for the CRB of TOA/RSS scheme, eq.(1) also hold for eq.(2). The only novelty is the second term in the numerator and the form of the first term in the denominator, which emphasize the geometry of devices performing TDOA observations, since TDOA observation are more geometry-dependent than TOA.

### *Comparison between TOA/RSS and TDOA/RSS*

For CRB computations, the channel measurement results given in [3] are used, obtained using a wideband direct sequence spread-spectrum transmitter and receiver. The transmitter outputs a 40MHz signal with code length of 1024 and 10mW of power. The measured channel parameters are $\sigma_{dB}/n_P = 2$ and $c\sigma_T = 1.8$. Four reference points are first placed in the corners of an 18m by 18m square, and the CRB for every coordinate in that region for TOA (Fig.2) and TOA/RSS (Fig.3) cases is computed. All reference points are capable of performing both TOA and RSS observation, hence $card(N_{TOA}) = card(N_{RSS}) = 4$. In the TDOA/RSS case (Fig. 4), the reference point with index 1 is placed in the center of the area and $card(N_{TDOA}) = 3$. In order to maintain the central symmetry of the plot, circular area with radius of $18/\sqrt{\pi} = 10$ m is used, thus preserving the same size of the area as in the TOA and TOA/RSS cases. The other three points are placed equidistantly around the circle.

The comparison between Fig.2 and Fig.3 reveals that TOA/RSS has better overall location accuracy than TOA. In particular, the use of RSS measurements mitigates the difficulties in locating the devices in the proximity of the reference points, which are inherent to the TOA-based schemes. The accuracy of the TDOA/RSS scheme (Fig.4) is inferior to TOA/RSS, as expected, due to the sacrifice of one TOA measurement. However, it also exhibits smoothened accuracy around the reference points.

Fig.5 shows the mean CRB over the entire area shown in Fig.2-4, for varying sizes of the area. Mean CRB for TDOA is also added, for comparison with TDOA/RSS. The *x*-axis shows the radius *x* of the circular region for TDOA and TDOA/RSS scheme. For TOA and TOA/RSS scheme, the mean CRB is computed over the square region having side equal to $x\sqrt{\pi}$, so that the corresponding area sizes are identical in all four cases. The benefit from the use of RSS measurements, in conjunction with TOA and TDOA, becomes evident at ranges below about 30m, for the given channel characteristics. This is the range a typical short-range wireless network, such as WiFi, UWB and WSN. For longer ranges, TOA/RSS and TDOA/RSS perform essentially the same as TOA and TDOA, respectively. It is interesting to examine the effect of the number of reference devices and their mutual positioning onto the location accuracy. This aspect will be discussed in the following section.

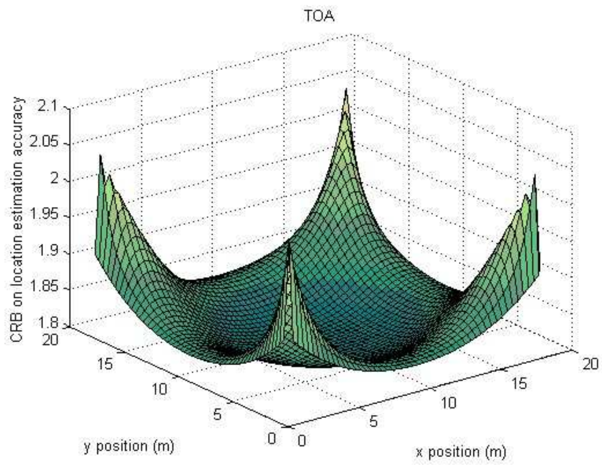


**FIGURE 2** THE CRB OF THE TOA SCHEME ESTIMATION WITH FOUR REFERENCE POINTS IN THE FOUR CORNERS ( $\sigma_{dB}/n_P = 2$ AND $c\sigma_T = 1.8$).

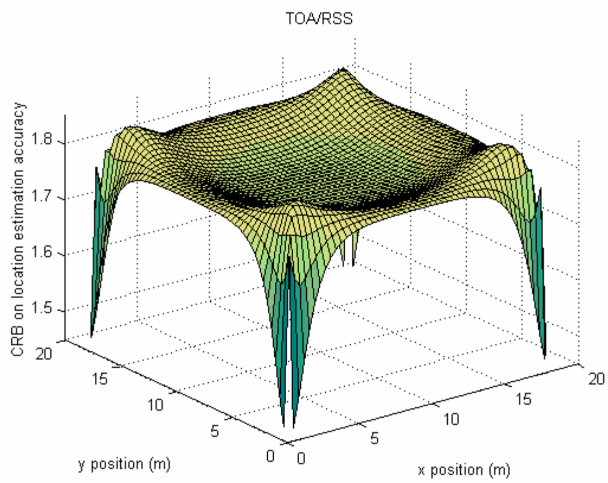


**FIGURE 3** THE CRB OF THE TOA/RSS SCHEME WITH FOUR REFERENCE POINTS IN THE FOUR CORNERS ( $\sigma_{dB}/n_P = 2$ AND $c\sigma_T = 1.8$).

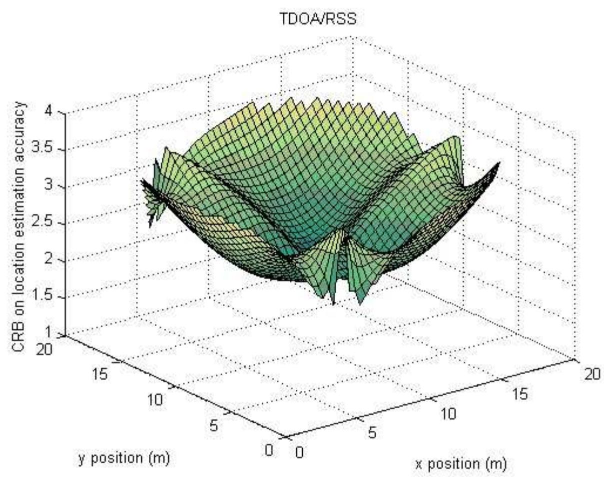


**FIGURE 4** THE CRB OF THE TDOA/RSS SCHEME WITH FOUR REFERENCE POINTS, ONE IN THE CENTER OF THE REGION ( $\sigma_{dB} / n_P = 2$ AND $c\sigma_T = 1.8$).

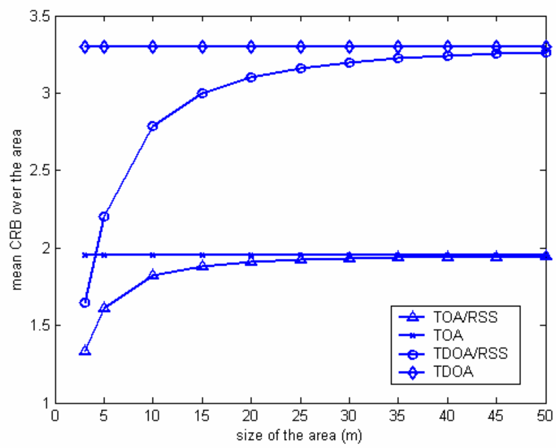


**FIGURE 5** MEAN CRB OF THE TOA, TOA/RSS, TDOA AND TDOA/RSS POINTS ( $\sigma_{dB} / n_P = 2$ AND $c\sigma_T = 1.8$).

## A HYBRID LOCATION ESTIMATION SCHEME (H-LES) FOR PARTIALY SYNCHRONIZED WSN

In this section, we propose a practical location estimation scheme for partially synchronized, heterogeneous WSN, comprised of sensor nodes (SN) that have very short transmission ranges (e.g., 30m) and no sense of timing, relay nodes (RN) that have simple routing capabilities and are not synchronized with the network, and mutually synchronized absolute position routers (APR). The SNs can be corresponded to the RN- devices in the ZigBee [7] standards, and the RNs to the RN+ devices. The proposed hybrid location estimation scheme (H-LES) is based on the combination of TDOA measurements between the SNs and the APRs that SNs can hear, and RSS measurements between the SNs and their neighboring RNs. The TDOA technique is used in order to mitigate the lack of synchronization between SNs and APs. The advantage of the H-LES is that it exploits both TDOA and RSS. The TDOA measurements are used to provide accuracy of location estimation in an unsynchronized network, while the use of RSS measurements at RNs enhances the accuracy within the neighborhood of RNs. In the H-LES, it is easy to quantify the trade-off between the number of synchronized routers, the density of relay nodes and the achievable location estimation accuracy. This gives an answer to an important design consideration.

Another advantage of the H-LES is that it takes into account the heterogeneity in communications ranges of network devices. The location estimation schemes available in the literature are based on the assumption that all the nodes have the same radio communication range. In other words, if node-A can hear node-B, node-B can also hear node-A. This is not realistic, because of the different transmission powers, battery capacities and overall complexity of the devices. Also, APR nodes are mutually synchronized, while RN and SN are not. In the following subsections, the description of the H-LES scheme is given. The CRB on the estimation accuracy of this scheme is discussed in the light of the performance trade-off between the number and density of APRs (i.e. TDOA measurements) and RNs (i.e. RSS measurements) involved. Some thoughts are also dedicated to the prospects for future work.

### *Description of H-LES*

The hybrid location tracking system, as illustrated in Fig.6, consists of three device types: SNs, RNs and APRs. The SNs are simple sensor devices with a radio circuitry of very short communication range (e.g., 10-30 meters). They are only capable of listening to and forwarding signals. The RNs are low-cost devices with simple routing capabilities and ability to measure the RSS of received signals. They also have a very short communication range (e.g., 10-30 meters). The APRs are stationary known-location devices with a precise central clock. The communication range of the APR is very long (e.g., 100 meters or longer). They are responsible for collecting messages from RNs and mobile SNs, and forwarding them to the Central Monitoring Unit (CMU) through an aggregation point. The APRs also distribute commands received from the central monitoring unit to the corresponding RNs and SNs.

#### *Message Types and Messaging*

Figure 6 illustrates signaling and timing of messages among system components for tracking the location of SNs. The numbers inside the parentheses indicate the time order of the messages. The indexes assigned to the APRs are used to identify them; and 0 index is used for the SN to be tracked. The following routine explains how messages are initiated and forwarded in the two APR case. The extension to the cases involving three or more APRs is straightforward, in which one extra message would arrive to the SN from each additional APR. For the sake of clarity, the scheduling of the broadcast beacons from the APRs is left out of the scope of this paper.

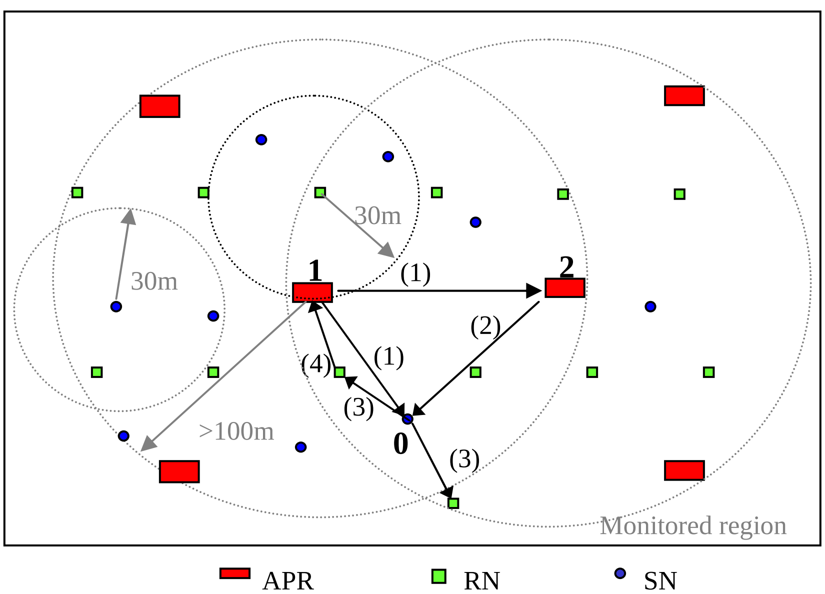


**FIGURE 6** MESSAGING IN THE H-LES

**The two APR case:** Messaging

1: The APR-1 broadcasts a beacon with a unique sequence number, message (1). The sequence number is used to prevent duplicate processing of the same message. The broadcast may be event-driven and instructed by the CMU, or it may be periodic.

2: The APR-2 and the sensor node SN-0, which are within the coverage area of APR-1, receive message (1).

3: The APR-2 modifies message (1) by appending its own ID, but maintaining the original sequence number. Afterwards, it broadcasts the modified message, (2).

4: Upon receiving a message from an APR, the SN-0 inserts its ID in the header, and forwards the message to its neighboring RNs, because it may not reach the APR directly due to its shorter communication range. The destination address for this message, (3), is the CMU.

5: The one-hop RN (could be one RN, like in the figure, or more) that receives message (3) inserts its ID to the message, and the RSS level of the signal. It then forwards the message, (4) for the CMU, through other intermediate RNs. These intermediate RNs do not need to modify the packet, but simply forward it until it reaches the destination. Note that by moving the RSS computation to the relay devices, mobile sensors are spared from measuring the RSS of signals from routers.

As described before, there are four different messages. The content of each message is given below.

**The two APR case:** Message Contents

1: Message (1) contains the time stamp of departure from APR-1, the ID of APR-1 and a unique sequence number to identify the broadcast beacon.

2: Message (2) contains the time stamp of departure from APR-1, the time stamp of departure from APR-2, the ID of APR-1, the ID of APR-2 and the same sequence number in message (1).

3: Message (3) contains the time stamp of departure from APR-1, the time stamp of departure from APR-2, the ID of APR-1, the ID of APR-2, the same sequence number in message (1) and the ID of mobile sensor SN-0.

4: Message (4) contains the time stamp of departure from APR-1, the time stamp of departure from APR-2, the ID of APR-1, the ID of APR-2, the same sequence number in message (1), the ID of mobile sensor SN-0 and the RSS of message (3).

*Timing Diagram*

Table-I presents the notations that are used in illustration of the timing of the messages in Fig.2. Taking the difference of the arrival times of messages (1) and (2) at SN-0 yields $t_{1,2} + t_{P2} + t_{2,0} - t_{1,0}$, which is an observation that is free from the unknown time offset $t_{0\_OFF}$. The CMU knows a-priori what $t_{1,2}$ is, and can derive the processing delay $t_{P2}$ from the difference of timestamps $t_1$ and $t_2$. So, the CMU can filter out $t_{1,2}$ and $t_{P2}$, and retrieve the observation of the *difference of the propagation times* $t_{i,0}$ and $t_{j,0}$, i.e. $T_{i,j} = t_{i,0} - t_{j,0}$. Note that with $m$ APRs and $n$ RNs, $m$-1 independent TDOA observations $T_{i,j}$ and $n$ independent RSS observations are available, respectively.

TABLE-I
TIMING NOTATIONS OF THE MESSAGES

| | |
|---|---|
| $t_i$ | Timestamp of departure at APR-*i* |
| $t_{i,j}$ | Time for the signal to traverse from APR-*i* to APR-*j* |
| $t_{Pi}$ | Processing delay at APR-*i* |
| $t_{i,0}$ | Time for the signal to traverse from APR-*i* to SN-0 |
| $t_{0\_OFF}$ | Time offset between APRs and the SN-0 |
| $d_{i,j}$ | Distance between APR-*I* and APR-*j* |
| $d_{i,0}$ | Distance between APR-*I* and SN-0 |

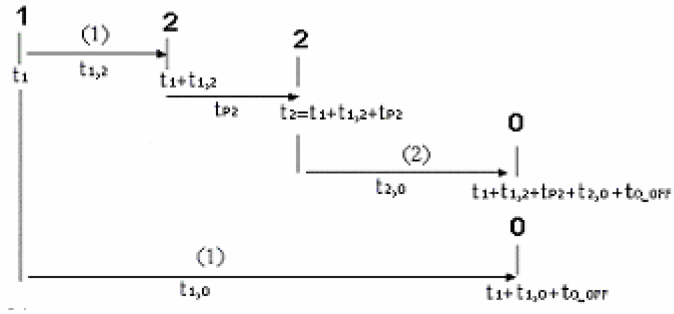


**FIGURE 7** TIMING DIAGRAM OF MESSAGES (1) AND (2)

The actual derivation of the location estimate is omitted here. Essentially, any estimator based on the above described set of TDOA observations and RSS observations can be used. The Maximum Likelihood Estimator (MLE), for instance, could easily be obtained along the lines of the derivation in [3]. The minimum achievable variance of any given estimator for H-LES was derived in Section 3.2.

### *CRB analysis*

The CRB of H-LES will correspond to the CRB of the TDOA/RSS scheme, derived in Section 3.2, with $card(N_{TDOA}) = m–1$ and $card(N_{RSS}) = n$, respectively, where $m$ is the number of APRs and $n$ is the number of RNs involved in the scheme. Figures 8-12 show $\sqrt{\sigma^2_{CRB}}$ for the H-LES, computed inside the 50m by 50m square region. The figures are produced using the same channel model as in Section 3.3. The RNs are located inside this square, while the APRs are located on the outer 100m by 100m region. At each point inside the inner square, the SN is assumed to be able to hear the signals of all APRs and the RNs.

The figures clearly show the difference between TDOA and RSS observations, and the benefits from their combination. TDOA observations are virtually independent on the distance to the APRs (except in the close proximity of APRs), and hence provide an almost uniform contribution to the estimation accuracy within their coverage region. The number of APRs involved in the estimation has major effect on the performance of H-LES. By comparing Figures 8, 11 and 12, one can infer that replacing two RNs by two APRs reduces the minimum achievable CRB in the region by roughly three times. RSS observations, on the other hand, have significant effect on the accuracy only in the proximity of RNs. Therefore, the number of APRs and the density of RNs are the network design parameters that can be fine-tuned to achieve the desired trade-off between the network installation cost and the achievable location estimation accuracy.

Allocating one APR to mitigate the lack of synchronization, the case of two APRs is the most inefficient, since 50% of APRs are not exploited for measurements. However, since only one APR needs to be sacrificed regardless of the total number of APRs used, the efficiency of the H-LES will get higher as the number of APRs in the network increases. It will asymptotically reach the CRB of the TOA/RSS location estimation scheme in a fully synchronized network in which the noise of the TOA observations is doubled. Note that for a direct use of the TOA in a fully synchronized network, the SNs must be able to directly communicate with the APRs. On the other hand, the H-LES removes this constraint.

It is evident from the comparison of Figures 10 and 11 that the impact of geometric conditioning of RNs with respect to APRs is measurable to the impact of the number of RNs involved. Hence, the mutual placement of APRs and RNs is an additional tool that can be used to provide the desired location estimation accuracy in the network, even if the number of RNs and APRs is fixed. Further analysis of the impact of geometric conditioning of APRs and RNS onto the location estimation accuracy in WSNs is the topic for future research.

## CONCLUSION

The hybrid approach to location estimation paves the way to take advantage of the benefits of TOA-based location estimation, while taking advantage of the short-range accuracy of RSS measurements. The analysis, based on the computation of the CRB for the TOA/RSS and TDOA/RSS hybrid schemes, indicates that the two schemes provide improved location estimation accuracy with respect to TOA and TDOA schemes, for communications ranges comparable to those in short-range wireless networks. In addition, they remove the inherent difficulties of TOA and TDOA schemes with respect to locating devices in the close proximity of the reference devices.

The contribution of the hybrid location estimation scheme (H-LES) for WSN, studied in this paper, with respect to the existing location estimation techniques consists in taking into account the heterogeneity of sensor networks, in terms of communication range, time synchronization and routing capabilities of network devices. H-LES is based on the heterogeneous network architecture, which consists in long-range fixed position routers, relay nodes and sensor nodes. The scheme requires full synchronization only among the fixed position routers. This hybrid scheme could be a good candidate for a positioning system for WSN.

The future work will focus on the investigation of the effect of mutual geometric conditioning of fixed routers and simple relay nodes from one hand, and the channel characteristics on the other hand, on the achievable location estimation accuracy, and the ways to its optimization.

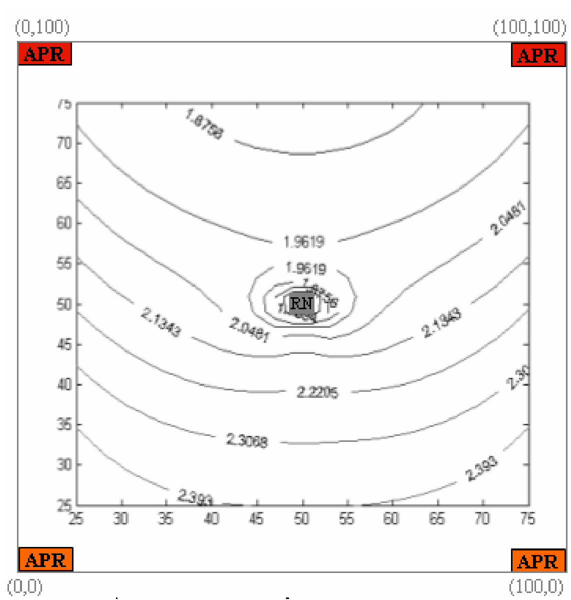


**FIGURE 8** THE CRB FOR 4 APRs AND 1 RN

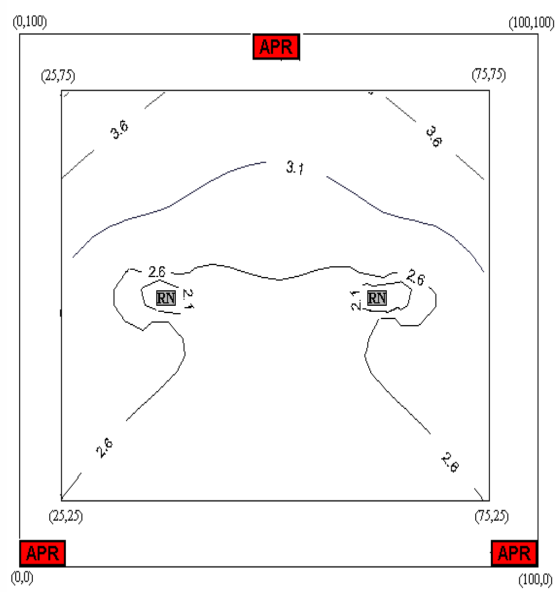


**FIGURE 9 –** THE CRB FOR 3 APRs AND 2 RNs

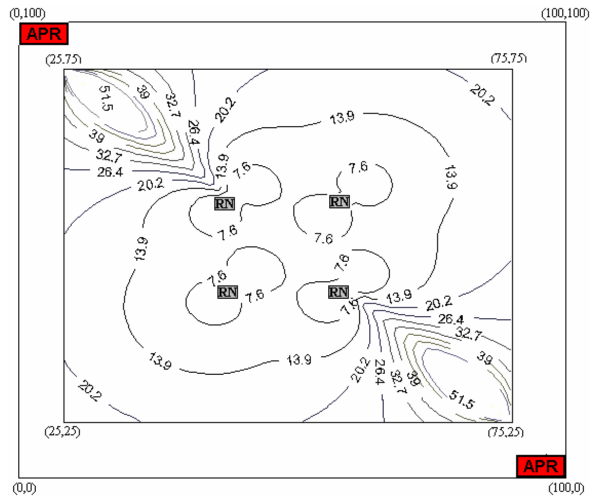


**FIGURE 10** THE CRB FOR 2 APRs AND 4 RNs

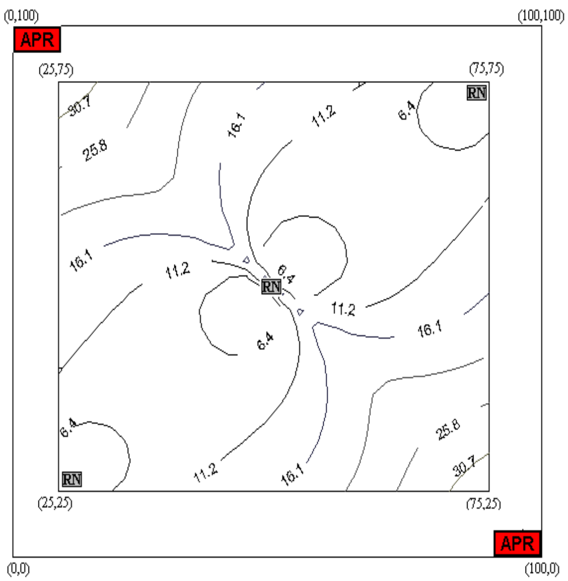


**FIGURE 11** THE CRB FOR 2 APRs AND 3 RNs

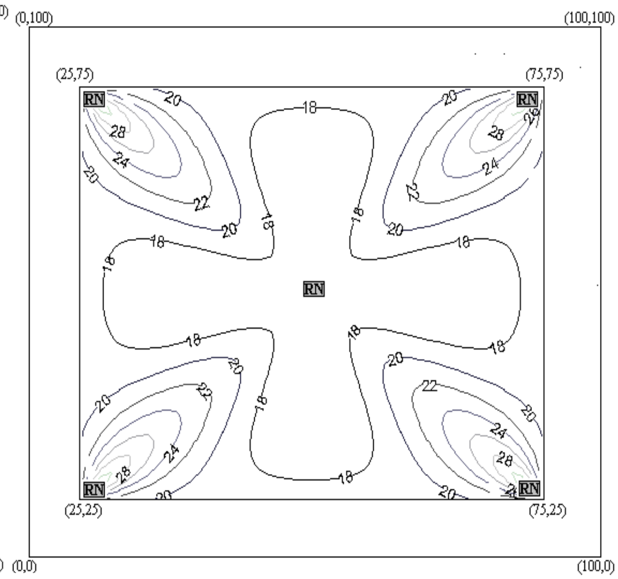


**FIGURE 12** THE CRB FOR 0 APR AND 5 RNs

## REFERENCES

[1] S. Tekinay et al., “Performance benchmarking for wireless location systems”, IEEE Communications Magazine, Vol. 36, No. 4, April 1998, pp. 72-76

[2] A. E. Leu and B. L. Mark, "An Efficient Timer-based Hard Handoff Algorithm for Cellular Networks," in *Proc. 2003 IEEE WCNC*, New Orleans, LA, March 16-20, 2003.

[3] N. Patwari, A. O. Hero, M. Perkins, N. S. Correal, R. J. O’Dea, “Relative Location Estimation in Wireless Sensor Networks,” *to appear in IEEE Trans. Signal Processing, 2003*.

[4] R. Hogg, A. Craig, *Introduction to Mathematical Statistics*, 5th edition, Prentice-Hall, 1995

[5] Z. Sahinoglu, A. Catovic, “A hybrid location estimation scheme (H-LES) for partially synchronized wireless sensor networks”, to appear in ICC 2004 (http://www.merl.com/papers/TR2003-142)

[6] A. Catovic, Z. Sahinoglu, “The Cramer-Rao Bounds of Hybrid TOA/RSS and TDOA/RSS Location Estimation Schemes”, to appear in the IEEE Communication Letters in 2004 (http://www.merl.com/papers/TR2003-143)

[7] P. Kinney, “ZigBee technology: wireless control that simply works”, IEEE 802.15.4 Task Group, http://www.zigbee.org/resources