Lightning: A Fast and Lightweight Acoustic Localization Protocol Using Low-End Wireless Micro-Sensors

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Abstract

Acoustic awareness is an important service in ubiquitous computing environments. This paper presents a fast lightweight acoustic event localization protocol, the Lightning protocol, to locate impulsive sound sources using arrays of wireless micro-sensors. This protocol utilizes domain-invariant knowledge of acoustic and electromagnetic wave propagation to efficiently reduce the number of contending sensors in the localization process. It incurs $O(1)$ *transmissions irrespective of the sensor density and guarantees* $O(1)$ *time delay in localization. Experiment results using UC Berkeley Motes demonstrate that the time delay for Lightning Protocol to locate hand clap sounds is in terms of milliseconds.*

1. Introduction

Recent technology advancements make possible massive deployment of wireless micro-sensors to form interconnected *Wireless Sensor Networks* (WSNs) for various military and civilian applications. Localization of acoustic events using wireless micro-sensors provides a low-cost solution to locate moving objects. It can be an integral part of ubiquitous computing environment.

Sound attenuates quickly in the air. To localize low intensity sound on land, dense placement of sensors are needed. To keep the system affordable, we use a large number of simple low cost sensors. On the other hand, the density of sensors also provides us with the opportunity to perform simple *proximity-based localization*, that is, identifying the closet sensor to the sound source. The following properties are desirable in the design of acoustic event localization (simplified as "acoustic localization" in the following) protocol in a wireless network of densely placed acoustic sensors.

- **Timeliness:** For many applications, it is critical to locate sound sources in short and bounded time periods, e.g., tracking a moving vehicle. It would be desirable that the localization algorithm can guarantee a short and constant ($O(1)$) time bound for real-time applications.
- **Lightweightness:** Micro-sensors are constrained in computation, storage and communication capability. Therefore, it is desirable for acoustic localization algorithms to be simple and efficient.
- **Acceptable Accuracy:** The accuracy of localization must be acceptable for the application. For example, a sentry service only needs to know if there is any unauthorized activity near the security zone.
- **Robustness:** There are two sources of uncertainty. First, the wireless medium is unreliable. Second, acoustic sources can be directional and of variable intensity; sound propagation is affected by blockage and multi-path effects. A robust localization algorithm needs to be able to handle the above uncertainties.
- **Energy-Efficiency:** Energy consumption must be considered in WSNs as most wireless micro-sensors are power constrained. It is desirable for a WSN to have prolonged post-deployment time with minimal service disruptions. An ideal energy-efficient localization algorithm should have minimal message exchanges in presence of acoustic events and conserve energy when there is none.

We propose a fast lightweight acoustic localization protocol called *Lightning* protocol that locates impulsive low-intensity sounds in indoor or urban environments using wireless micro-sensors.

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Lightning Protocol is a proximity based protocol. It exploits the domain-invariant characteristics of acoustic and electromagnetic wave propagation.

Like most acoustic localization protocols, it also uses acoustic *Time-Of-Arrival* (TOA) at sensors. However, it does not require clock synchronization. Nor does it use data packets for communication. In fact, it allows overlapping wireless broadcasts that greatly simplifies the implementation. This Protocol is robust in the sense that the sound source can be directional and of variable intensity; sound propagation can be affected by blockage and multi-path effects. Lightning Protocol can also be energy efficient in the sense that sensors turn on their radio only when there is an acoustic event.

We implement Lightning Protocol on U.C. Berkeley Motes[1][2] and compare it with a *Data Packet*(DP)-based scheme. The Lightning Protocol code has a very small footprint: 5330 bytes in ROM and 187 bytes in RAM. In Section 6, experimental results show that when using Lightning Protocol, delay for localization is less than $14ms$. In 81.4% of the localization trials, there is only *one* wireless broadcast involved. The accuracy is comparable or better than that of an ideal DP scheme that never has collisions.

The rest of the paper is organized as follows. In Section 2, we first give a brief overview of existing solutions to acoustic localization. In Section 3, we motivate the proposed solution by closely examining the acoustic characteristics in our application scenarios. The Basic Lightning Protocol and its energy-efficient version are described in Section 4 and Section 5 respectively. Experimental results are presented in Section 6. Finally, we conclude the paper in Section 7.

2. Related Work in Acoustic Localization

Generally, there are two approaches. The first category requires the use of some powerful nodes. The second is a pure *proximity-based localization* approach. With densely deployed sensors, proximity-based localization achieves acceptable accuracy. More importantly, since proximity-based localization requires only TOA comparisons, it is lightweight and can be carried out using only low-end micro-sensors. As we will show later, there is no need to synchronize the clocks of sensors either.

Examples of the first category of approaches include [3][4][5][6]. In [3], a Particle-Filtering style recursive estimation algorithm is devised to asymptotically approach the moving target's track over time. In [4][5][6], *Maximum Likelihood*(ML)-based localization methods are proposed based on amplitude or TOA readings of an array of sensors. In [4], sound sources are assumed to be omni-directional and the attenuation model is known. Each sensor estimates its distance to sound source based on the detected acoustic amplitude. In [5], each sensor reports its local TOA, and the algorithm scans the whole monitored area to find the grid point that best matches the TOA readings of the sensor array. Simon *et. al.*[6] implement a sniper gun localization system based on TOA of muzzle blast using Maximum Likelihood estimation techniques. Most commercial gunshot localization systems make use of the shock wave created by a bullet traveling at supersonic speed [7].

Examples of proximity-based localization approach includes [8][9][10]. In [8][9], all sensors detecting an impulsive sound exchange their sound intensity readings or TOAs using multi-hop data communication. The sensor with the best reading wins the election. Chen *et al.*[10] devise a back-off based method to accelerate the election process. This scheme works well if the sound sources are omni-directional and of known intensity.

Lightning Protocol does not use data packets. To the best of our knowledge, it is the first scheme that guarantees a constant delay bound, and is robust to directionality of sound sources and the variation of sensor density.

3. Design Considerations

3.1. Acoustic Characteristics

In this paper, we consider the problem of acoustic localization of low-intensity impulsive sound sources on land. The properties of the acoustic signal are listed as follows:

P1 Impulsive sounds: Impulsive sounds (called *beeps*) are defined as acoustic signals with clearly detectable onset and thus their TOAs can be measured, *e.g.*, foot steps.

P2 Low and varying Intensity: Everyday acoustic events are usually of low intensity. Furthermore, the intensity may vary and is not known *a priori*. Detectable distances of these events are usually on the order of tens of feet.

P3 Blockage and Echos: In indoor or urban environment, there are blockages (*e.g.* walls, buildings) that prevent direct line-of-sight propagation of acoustic signal. At farther distances, an acoustic signal may travel indirect paths to a sensor due to reflections.

P4 Directionality: Acoustic sound sources are in general not omni-directional (*e.g.* person speaking).

Directionality in the acoustic field implies that "closest" is not equivalent to "loudest".

Properties P2 and P3 requires us to use densely placed micro-sensors. Properties P1 and P4 requires us to use TOA as the primary measurement. For impulsive sound sources, as long as direct line-of-sight to sensors is available, TOA is proportional to the distance between the sound source and sensors. It is independent of the directionality and loudness of the sound.

3.2. Assumptions

Unlike many existing acoustic localization approaches, we do not assume omni-directional sound sources. Nor do we assume *a priori* knowledge of the sound intensity or acoustic propagation models. However, we make the following assumptions on sound sources and hardware devices:

- The closest sensor should always be able to hear the sound, no matter what direction it is oriented toward the sound source (a more quantitative definition is given in Section 4.3).
- The sound propagation medium (say, the air) is stable and ensures uniform acoustic propagation speed, denoted by v.
- Wireless transmission range is at least twice as large as the acoustic sensing range. Therefore, all sensors that overhear the same sound can directly communicate with each other[1].
- Each micro-sensor is equipped with a half-duplex radio transceiver with configurable *Radio-Frequency* (RF) channel that can be changed during runtime[2].

4. Basic Lightning Protocol

4.1. Intuition

Our goal is to devise a proximity-based localization protocol that quickly and efficiently identifies the sensor closest to the sound source.

As mentioned in Section 3, TOA measurements based on onset detection are robust to directionality of sound sources, reflections and multi-path propagation of acoustic signal. One straightforward localization algorithm is to compare the TOAs at each sensor. The one with the smallest TOA reading is determined to be closest to the sound source. However, this approach suffers from two main problems, (*i*) requirement of clock synchronization as each sensor time-stamps the TOA based on its local clock; and (*ii*) increasing overhead with respect to the sensor density.

Our proposed Lightning Protocol is a self-synchronized protocol and only involves $O(1)$ messages to elect the closest sensor. The basic idea of Lightning Protocol is inspired by observing the lightning phenomenon in nature. When a lightning bolt strikes, people *see* the lightning much earlier than they *hear* the accompanying thunder. This is because electromagnetic waves travel much faster than sound waves. To apply such a domain-invariant characteristic to the localization problem, we notice that an acoustic signal arrives at the closest sensor (say, S_1) first and thus it has the earliest TOA. If S_1 can *immediately* transmits a *Radio Frequency* (RF) signal notifying all other sensors that it hears the sound, all other sensors can decide that they are farther away from the sound source even before the sound reaches them.

However, there is one difficulty in applying the above idea to acoustic localization, *i.e.*, wireless transmissions are usually subject to collisions. In particular, if there are several sensors at similar distances to the sound source, broadcasting data packets can cause collisions that prevent the immediate notification. To solve this problem, we propose the use of raw RF burst to signal the arrival of sound wave. Presence of RF bursts indicates detection of acoustic signal at certain sensors. RF bursts can be detected by measuring the received radio energy[11].

Next, we describe the detailed design of Basic Lightning Protocol.

4.2. Protocol Details

For ease of presentation, we assume sensors are placed at regular grids on the plane. Without loss of generality, we assume square grid in this paper, as shown in Fig. 1(a). Fig. 1(b) shows another regular grid layout, which is hexagonal. Extension of Lightning Protocol to *random layouts* is under way, and is to be presented in our upcoming future publications. In regular grid layout, each sensor is assigned a color i, as shown in Fig. 1 (for square, $i \in \{1,2,3,4\}$; for hexagonal, $i \in \{1,2,3\}$). The color assignment guarantees that for any point in the plane, the enclosing sensors are of distinctive colors. As explained later, such a color assignment guarantees the uniqueness of localization results.

Let T_b be the minimum duration that an RF burst must sustain in order to be robustly detected. And we call an impulsive sound event a *beep*. The operations of the Basic Lightning Protocol go as follows:

1. All sensors are initially in RF *listening mode*.

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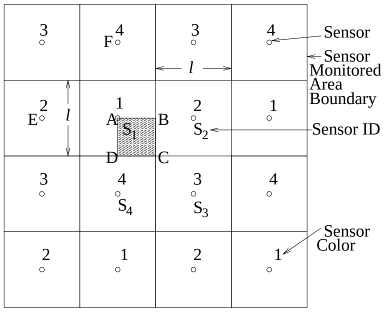
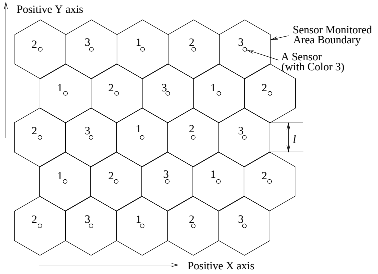
[1] This is practical because we are interested in low-intensity sounds.

[2] For example, the latest generation of U.C. Berkeley Motes support runtime reconfiguration across 868∼916MHz range [1].



(a) Square



(b) Hexagonal

Figure 1. Regular Sensor Grid Layout Examples

2. While in the listening mode, if a beep is *recognized*[3], a sensor with color i switches immediately to RF *bursting mode* and broadcasts *without backoff* an RF burst of $i \cdot T_{burst}$ duration (T_{burst} is an implementation-specific constant).

   Immediately after the burst, the sensor switches back to RF listening mode and samples the wireless medium for T_b. If no other RF burst is recognized, it wins the election and enters the *elected mode*. Otherwise, it loses the election and enters the *suppressed mode*. In both cases, a sensor sets up a timer of length T_{reset}^{basic}.

3. At any time during RF listening mode, if an RF burst is recognized, the sensor fails the election and enters the suppressed mode. Meanwhile, the sensor sets up a timer of length T_{reset}^{basic}.

4. After the localization is completed (when timer T_{reset}^{basic} expires), all sensors return to the listening mode.

T_{reset}^{basic} is a preset constant for all sensors to reset their state meanwhile ensure consistency. The setting of T_{reset}^{basic} will be explained in further detail later.

As mentioned earlier in Section 3.2, we assume micro-sensors can switch between multiple RF channels during runtime. This allows us to use a separate RF channel for burst. When a sensor is not elected, it only listens and bursts at the RF burst channel. Once elected, a sensor switches to data communication channel to transmit localization results. Fig. 2 summarizes the state transitions of the Basic Lightning Protocol.

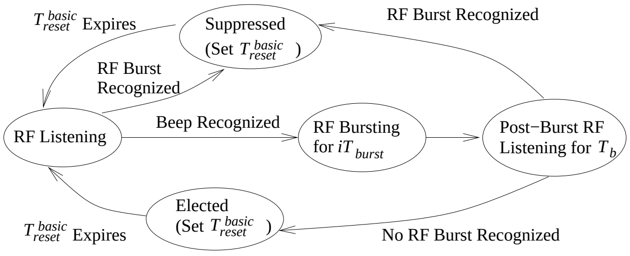


Figure 2. State Transition Diagram of Basic Lightning Protocol for a Sensor with Color i

4.3. Properties of Basic Lightning Protocol

In this section, we prove that Basic Lightning Protocol will elect a unique sensor within $O(1)$ time delay, and the elected sensor is among the closest sensors enclosing the sound source.

For now, we assume there is only one sound event (beep). The case of multiple sound events is discussed in Section 6.5. Without loss of generality, we consider a square sensor grid, and the sound source location $p = (x, y) \in \square ABCD$ (see Fig. 1(a), $\square ABCD$ refers to the shaded square area). The distances between the sound source and the four adjacent sensors S_1, S_2, S_3 and S_4 (colored 1,2,3 and 4 respectively) are $d_1(p)$, $d_2(p)$, $d_3(p)$ and $d_4(p)$ respectively. $d_{other}(p)$ is the distance between the sound source location p and the closest sensor other than $S_1 \sim S_4$. We assume the sensor density is high enough such that at any position $p \in \square ABCD$, a beep is recognizable to all sensors $S_1 \sim S_4$ regardless of its directionality. As RF waves travel a lot faster than acoustic signals, we ignore the propagation delay of RF burst in our analysis. Let t_{recg} be units of time for a sensor to *recognize* a beep, $t_{recg} \in [0, \Delta_{recg}]$, *i.e.* Δ_{recg} is the maximum duration to recognize a beep. The notations used in the analysis are summarized in Table 1.

Before delving into the derivation, we first present the key results. Theorem 1 states that Basic Lightning Protocol elects a single sensor and the localization error is bounded; Corollary 1 gives the upper bound of *election delay*. Election delay refers to the time duration since the beep takes place till every sensor enters either elected or suppressed mode.

Theorem 1 (Uniqueness of Sensor Election) *If* $T_{burst} \geq 2T_b$ *and square grid edge length* $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$*, Basic Lightning Protocol*

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[3] "*Recognize*" refers to the time instance when the arriving beep is detected by the signal recognition module and reported to the localization module.

t_{recg}	a random variable denoting the time to recognize a beep
$0, \Delta_{recg}$	the minimum and maximum possible time to recognize a beep
T_{burst}	the RF burst duration for a sensor colored 1
iT_{burst}	the RF burst duration for a sensor colored i
T_b	minimum duration that an RF burst must sustain in order to be recognized
$T^{\star}_{reset}$	time to reset to initial mode from suppressed or elected mode. $\star$ corresponds to a specific version of Lightning Protocol
$T^{\star}_{bound}$	election delay bound, the time bound from the beep takes place to all sensors enter elected or suppressed mode. $\star$ corresponds to a specific version of Lightning Protocol
$T^{\star}_{bound} + T^{\star}_{reset}$	turn-around time
R^{max}_{beep}	the maximum audible radius of a beep
p	(x, y) location of the sound source, $p \in \Box ABCD$, see Fig. 1(a)
l	grid edge length, see Fig. 1(a)
$d_1(p) \sim d_4(p)$	distance between the sound source to the four adjacent sensors in the grid
$d_{other}(p)$	distance between the sound source and the closest sensor other than the four adjacent sensors
$d(p)$	distance between the sound source and the elected sensor
v	propagation speed of acoustic waves

Table 1. Notation used in the analysis

elects exactly one sensor among $S_1 \sim S_4$. Furthermore, the distance $d(p)$ between the sound source location p and the elected sensor satisfies $d(p) \leq d_1(p) + (\Delta_{recg} + T_b)v$.

Corollary 1 (Election Delay Bound) *If $T_{burst} \geq 2T_b$ and $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$ and a beep takes place at time 0, Basic Lightning Protocol incurs an election delay no greater than $T^{basic}_{bound} = \frac{\sqrt{2}l}{2v} + 2\Delta_{recg} + 4T_{burst} + 2T_b$.*

To prove the above results, we first present the following lemmas.

Lemma 1 *If square edge length $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$, only S_1, S_2, S_3 and S_4 may burst, all other sensors are suppressed.*

Proof:

Recall that $d_{other}(p)$ is the distance between p and the closest sensor other than $S_1 \sim S_4$. $\inf_{\forall p \in \Box ABCD}\{d_{other}(p)\} = l$, and this value is reached only when $p = A$. The sensor is either at point E or F (Fig. 1(a)). On the other hand, $\sup_{\forall p \in \Box ABCD}\{d_1(p)\} = \frac{\sqrt{2}}{2}l$, and this value is reached only when $p = C$. Hence, $\forall p \in \Box ABCD$, $d_{other}(p) - d_1(p) > \frac{2-\sqrt{2}}{2}l$. When $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$, we have $\forall p \in \Box ABCD$, $\frac{d_{other}(p) - d_1(p)}{v} > (\Delta_{recg} + T_b)$. Hence, when the sound wave reaches any of the sensors other than $S_1 \sim S_4$, S_1 should have either recognized the beep and burst for at least T_b units of time, or should have been suppressed by a burst from S_2, S_3 or S_4. In both cases, any sensor other than $S_1 \sim S_4$ would be suppressed.

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Definition 1 *When the beep is at a location that is equidistant or nearly equidistant to multiple sensors, due to randomness of beep recognition duration t_{recg}, the closest sensor may not always burst first and suppress all other sensors, i.e. the elected sensor may be not the closest sensor. Such set of locations form a* Non-Deterministic Area. *However, we shall see the localization error incurred by non-deterministic area is* small *(Theorem 1). Specifically, We define non-deterministic area V as:*

$$\begin{aligned} V \;&:=\; \Big\{p\Big|p \in \Box ABCD \text{ and } \frac{d_1(p)}{v} + \Delta_{recg} + T_b \\ &\geq\; \min\Big\{\frac{d_2(p)}{v}, \frac{d_3(p)}{v}, \frac{d_4(p)}{v}\Big\}\Big\} \end{aligned}$$

Lemma 2 *When $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$, if $p \in \Box ABCD$ and $p \notin V$, then only S_1 would burst and thus win the election.*

Proof:

By Lemma 1, the only sensors that may compete with S_1 are S_2, S_3 and S_4. $p \in \Box ABCD$ and $p \notin V$ means $\frac{d_1(p)}{v} + \Delta_{recg} + T_b < \min\left\{\frac{d_2(p)}{v}, \frac{d_3(p)}{v}, \frac{d_4(p)}{v}\right\}$. Therefore, by time $d_1(p)/v + \Delta_{recg}$, S_1 should have recognized the beep and started bursting, meanwhile the beep has not yet reached S_2, S_3 and S_4. By time $\frac{d_1(p)}{v} + \Delta_{recg} + T_b$, S_1 should have already burst for T_b duration, while the beep has not yet reached any of S_2, S_3 and S_4. Therefore, $S_2 \sim S_4$ are suppressed by S_1.

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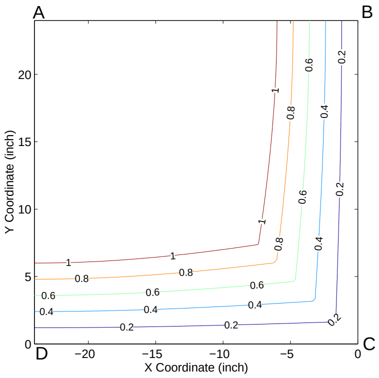

Figure 3. Area lower-right to the contour is the non-deterministic area within $\square ABCD$ of Fig. 1(a), where $\Delta_{recg} + T_b = 0.2, 0.4, 0.6, 0.8$ and $1ms$ respectively. Assume sound propagation speed $v = 1ft/ms$ and edge-length of $\square ABCD$ to be $2ft$.

On the other hand, by the same argument, we can prove that if $p \in V$, S_2, S_3 or S_4 may burst before the closest sensor S_1, or even suppress S_1. In Fig. 3, we plot non-deterministic area V for square $\square ABCD$ (edge-length equals 2 ft), under different $\Delta_{recg} + T_b$. To prove Theorem 1, note that by the color assignment shown in Fig. 1(a), $S_1 \sim S_4$ each has a distinct color. Without loss of generality, suppose S_1, S_2, S_3 and S_4 are of color 1, 2, 3and 4 respectively. Then we have the following lemma:

Lemma 3 *If $T_{burst} \geq 2T_b$, then after a beep, if multiple sensors burst, the one with "largest color number" always wins the election.*

Proof:

According to Lemma 1, if multiple sensors burst after a beep, the total number of bursting sensors can only be 2, 3 or 4.

Case 1: *2 sensors burst.* We denote them as S_i and S_j, where $i, j \in \{1, 2, 3, 4\}$ and $i > j$. Suppose S_i bursts during time interval $[t_i^0, t_i^0 + iT_{burst}]$ and S_j bursts during $[t_j^0, t_j^0 + jT_{burst}]$. Then we must have $|t_i^0 - t_j^0| < T_b$, otherwise, the later burst would be suppressed. (i) If $t_i^0 < t_j^0$, after S_j stops bursting, burst from S_i will last for

$$\begin{array}{rl} & iT_{burst} - jT_{burst} - (t_j^0 - t_i^0) \\ = & (i-j)T_{burst} - (t_j^0 - t_i^0) \\ > & T_{burst} - T_b \geq 2T_b - T_b = T_b \end{array}$$

The last "$\geq$" is due to $T_{burst} \geq 2T_b$. Hence, S_j has enough time to recognize S_i's burst after its own burst, and realizes that it has lost the election. (ii) If $t_i^0 \geq t_j^0$, after S_j stops bursting, burst from S_i will last for $iT_{burst} - (jT_{burst} - (t_i^0 - t_j^0)) = (i-j)T_{burst} + (t_i^0 - t_j^0) \geq T_{burst} \geq 2T_b > T_b$. Hence, S_j has enough time to recognize S_i's burst after its own burst, and realize that it has lost the election. Therefore, according to $(i)(ii)$, S_i would always win.

Case 2: *3 and 4 sensors burst.* The same reasoning as in Case 1 can be applied here.

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Now we are in the position to prove Theorem 1. Theorem 1 states that a unique sensor is elected in Basic Lightning Protocol and the localization error is bounded.

Proof:

By Lemma 1, the only possible competing sensor are $S_1 \sim S_4$. By Lemma 2, Theorem 1 sustains when $p \notin V$. When $p \in V$, by Lemma 3, only one sensor wins.

If the winning sensor is S_1, $d(p) = d_1(p) \leq d_1(p) + (\Delta_{recg} + T_b)v$. If it is S_2, $d(p) = d_2(p) \leq d_1(p) + (\Delta_{recg} + T_b)v$, otherwise S_1 would have suppressed S_2. The same reasoning applies when the winning sensor is S_3, S_4.

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From Theorem 1, we can prove that the election delay is bounded (Corollary 1) as follows:

Proof:

The winning sensor starts the burst no later than $\frac{d(p)}{v} + \Delta_{recg}$. For the square sensor grid layout, the longest bursting time is $4T_{burst}$. Hence, by time $\frac{d(p)}{v} + \Delta_{recg} + 4T_{burst} + T_b$, the winning sensor should have entered the elected mode. Since the winning sensor has already stopped bursting by that time, all other sensors must have entered the *suppressed mode*. Therefore, the election process completes no later than:

$$\begin{array}{rl} & \frac{d(p)}{v} + \Delta_{recg} + 4T_{burst} + T_b \\ \leq & \frac{d_1(p)}{v} + (\Delta_{recg} + T_b) + \Delta_{recg} + 4T_{burst} + T_b \\ \leq & \frac{\sqrt{2}l}{2v} + 2\Delta_{recg} + 4T_{burst} + 2T_b \\ = & T_{bound}^{basic} \end{array}$$

The first "$\leq$" is due to Theorem 1.

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If a beep takes place at time 0, and suppose the maximal audible range of the beep is R_{beep}^{max}, by time $\frac{R_{beep}^{max}}{v} + \Delta_{recg}$, it would have been recognized by the farthest away sensor. On the other hand, according to Corollary 1, every node either enters suppressed mode or elected mode by time T_{bound}^{basic}. Assuming a beep is recognized only when an onset is detected preceded by a period of silence, we can reset every sensor to initial listening mode at time $\max\{\frac{R^{max}_{beep}}{v} + \Delta_{recg}, T^{basic}_{bound}\}$. Therefore, as a conservative approach, it is safe to let $T^{basic}_{reset} = \max\{\frac{R^{max}_{beep}}{v} + \Delta_{recg}, T^{basic}_{bound}\}$. Hence, by time $T^{basic}_{bound} + T^{basic}_{reset}$ (called *turn-around time*) all sensors are reset to RF listening mode.

5. Energy-efficient Lightning Protocol

The Basic Lightning Protocol requires a sensor to keep its radio active all the time either in RF listening mode or RF bursting mode. This can be costly in energy consumption. To save energy, a naive approach would be that a sensor turns on its RF module only when an acoustic beep is recognized. It turns off the radio after localization is completed (with results sent back to the sink if necessary). However, consider the case when the acoustic beep arrives at the closest sensor S^* earlier than sensor S, such that S^* recognizes the beep, say, $11ms$ earlier than S. If the burst of S^* lasts for only $10ms$, then S would not have turned on its RF module before S^* finishes its burst. In this case, the burst from S^* cannot suppress S. Consequently, S considers itself elected as well.

5.1. Protocol Details

To handle the above problem and conserve energy, we propose an Energy-Efficient Lightning Protocol. The idea is, upon recognition of a beep, a sensor turns on RF and listens for a period of time before it starts to burst. Let the maximal audible radius of a beep be R^{max}_{beep}. If a sensor recognizes a beep, after $\Delta_{defer} = \frac{R^{max}_{beep}}{v} + \Delta_{recg}$, the beep must have reached and been recognized by the farthest sensor within the R^{max}_{beep} radius. That is, after Δ_{defer}, any sensor that can hear the beep should have turned on its RF module and switched to RF listening mode. The operations of the Energy-Efficient Lightning Protocol are as follows:

1. All sensors are initially in RF *sleeping mode.*
2. While in RF sleeping mode, if a beep is recognized, a sensor turns on its RF module to RF *listening mode* immediately for a duration of $\Delta_{defer} = \frac{R^{max}_{beep}}{v} + \Delta_{recg}$.
3. If no RF burst is recognized in the Δ_{defer} period, a sensor with color i enters RF *bursting mode* and transmits *without back-off* a burst of $i \cdot T_{burst}$ duration.

   Immediately after the burst, the sensor switches back to RF listening mode and samples the wireless medium for T_b. If no other RF burst is recognized, the sensor decides that it wins the election and enters the *elected mode.* Otherwise, it loses the election and enters the *suppressed mode.* In both cases, a sensor sets up a timer of length T^{ee}_{reset}.

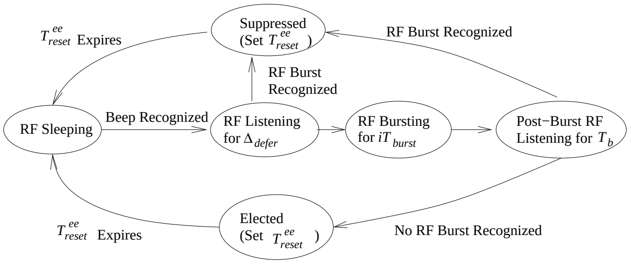


Figure 4. State Transition Diagram of Energy-Efficient Lightning Protocol

4. At any time during RF listening mode, if an RF burst is recognized, the sensor fails the election and enters the suppressed mode. Furthermore, the sensor sets up a timer of length T^{ee}_{reset}.
5. After the localization is completed (after timer T^{ee}_{reset} expires), sensors return to the RF sleeping mode.

T^{ee}_{reset} is a preset constant for all sensors to reset to initial state. The setting of T^{ee}_{reset} will be explained in further detail later.

Fig. 4 illustrates the state transition of Energy-Efficient Lightning Protocol. Compared with Fig. 2, an extra RF sleeping mode is introduced. In RF sleeping mode, a sensor can put its radio module to low power states to conserve energy.

5.2. Analysis of Energy-Efficient Lightning Protocol

In this section, we prove that Energy-Efficient Lightning Protocol preserves the desirable properties as the Basic Lightning Protocol, *i.e.*, $O(1)$ transmissions and bounded election delay.

Uniqueness of Sensor Election

Theorem 2 *Lemma 1∼3 and Theorem 1 remain valid for Energy-Efficient Lightning Protocol.*

Proof:

According to Energy-Efficient Lightning Protocol, every sensor delays Δ_{defer} after it recognizes the beep. By the time the first RF burst starts, all sensors that can hear the beep would have switched to RF listening mode. From thereon, the protocol proceeds as the Basic Lightning Protocol. In other words, it is equivalent to that the beep takes place Δ_{defer} units of time later than the actual beep with every sensor running Basic Lightning Protocol. Therefore, all proofs in Lemma 1∼3 and Theorem 1 sustain.

■

Election delay Similarly, the following corollary holds.

Corollary 2 (Election Delay Bound) *If $T_{burst} \geq 2T_b$ and $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$ and a beep takes place at time 0, Energy-Efficient Lightning Protocol incurs an election delay no greater than $T^{ee}_{bound} = T^{basic}_{bound} + \Delta_{defer} = \frac{\sqrt{2}l}{2v} + \Delta_{defer} + 2\Delta_{recg} + 4T_{burst} + 2T_b$, where $\Delta_{defer} = \frac{R^{max}_{beep}}{v} + \Delta_{recg}$.*

Similar to the argument for T^{basic}_{reset} in Section 4.3, assume the maximal audible range of the beep is R^{max}_{beep}, a conservative value for the time to reset sensors to initial sleep mode from suppressed or elected mode T^{ee}_{reset} is $T^{ee}_{bound} - \Delta_{defer}$. Therefore, by time $T^{ee}_{reset} + T^{ee}_{bound}$ (called *turn-around time*), all sensors are reset to the initial RF sleeping mode.

Energy consumption In the Energy-Efficient Lightning Protocol, sensors are active (with radio on) only during the localization period. Since the localization time is short, the energy consumption is small. For example, two AA batteries can sustain a U.C. Berkeley Mote with its radio active for 59 hours. In our implementation (Section 6.1), a burst lasts $14ms$ at the most. The RF listening time $\Delta_{defer} \approx 49ms$ (with $R^{max}_{beep} = 15m$). Approximately, with two AA batteries, over 3.4 million acoustic events can be localized using Energy-Efficient Lightning Protocol.

In what follows, unless otherwise specified, the term "Lightning Protocol" refers to Energy-Efficient Lightning Protocol.

5.3. A Quantitative Comparison with Data Packet(DP)-based Scheme

Let n be the number of sensors hearing the acoustic beep. Let T^{light}_{elec} and T^{data}_{elec} be the election delay of Lightning Protocol and a DP scheme respectively. We have $T^{light}_{elec} \leq T^{ee}_{bound}$ and $T^{ee}_{bound} \sim O(1)$ (Corollary 2), therefore $T^{light}_{elec} \sim O(1)$, which is the best possible for any localization protocol. $T^{ee}_{bound} \sim O(1)$ for the following reasons: by the definition of T^{ee}_{bound} given in Corollary 2, the only parameter that is relevant to total number of sensors n is l, *i.e.* the sensor grid edge length. However, as n increases, l becomes smaller, which makes T^{ee}_{bound} smaller. One may argue that in Theorem 1,2 and Corollary 1,2, it is required that $l > \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$. This requirement is needed to guarantee only *one* sensor is elected. In cases that $l \leq \frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$, there may be multiple winners within $\frac{2}{2-\sqrt{2}}(\Delta_{recg} + T_b)v$ radius to the sound source (there is no winner outside this circle). But in this case, with similar approach, it can be proved that both election delay and turn-around time ($T^{ee}_{bound} + T^{ee}_{reset}$) are still $O(1)$. The same conclusion also applies to Basic Lightning Protocol.

For DP schemes, sensors that hear the beep must contend for the wireless medium to broadcast their TOA readings. If an IEEE 802.11 like MAC protocol is adopted to resolve the channel contention, the expected number of data packet collisions before the *first* successful data packet broadcast grows exponentially with the number of contending sensors[12], *i.e.*, $\Omega(c^n)$, where c is a constant > 1. For wireless sensors equipped with half-duplex radio, once a transmission starts, it lasts till the entire packet is transmitted. Collisions are detected by lack of acknowledgments at the sender. Let T_{pack} be the time to transmit a data packet. Therefore, the expected delay before the first successful data packet broadcast is $\Omega(c^n \times T_{pack}) = \Omega(c^n)$. The expected election delay $\mathbf{E}[T^{data}_{elec}]$ to get the data packet with earliest TOA is strictly no less than $\Omega(c^n \times T_{pack})$. Therefore, $\mathbf{E}[T^{data}_{elec}] \sim \Omega(c^n)$.

One may argue that MAC contention can be alleviated by reducing the radio range in data communication. In this case, the assumption that radio range is at least twice as large as the acoustic sensing range may no longer hold. Sensors overhearing the same acoustic event cannot reach each other directly. Therefore, multi-hop communications are needed to elect the closest sensors. As a result, the election delay is thus the sum of single-hop election delay and the delay incurred by multi-hop forwarding of data packets. When the sensors get denser (*i.e.* when n increases), the election delay increases monotonically anyway.

6. Experiments and Comparisons

6.1. Overview

To study the performance of the proposed Lightning Protocol, we implement it on U.C. Berkeley Motes. The transmission/reception of RF bursts is supported by the RF hardware of Motes[11]. The machine code size is small. Including both acoustic sensing and Lighting Protocol module, linked with TinyOS (Mote's operating system), the final total footprint is 5330 bytes in ROM and 187 bytes in RAM.

We conduct several experiments to evaluate Lightning Protocol and compare it against an ideal DP scheme. Video clips of the demo are available at [13]. The experimental setup is as follows:

16 motes are placed on square grid points, each monitoring a square area of $4ft \times 4ft$. To evaluate the ro-

bustness of the protocol, we use upright speaker oriented along the X-axis (see Fig. 5(a)) as directional sound source. Fig. 5(b) provides a top-view of the layout of sensors, sound source orientation and locations. Fig. 5(c) demonstrates the irregular intensity field of the speaker playing a hand clap sound.

As a baseline, we also implement a *Data Packet*(DP) *Localization Protocol*. The operations of DP protocol are described in Fig. 6. Both Lightning Protocol and DP protocol use the same TOA recognition module.

```
1. /* When a beep takes place */
2.     All sensors report their detected TOAs;
3.     Pick the sensor with the earliest TOA as the closest sensor;
```

Figure 6. Data Packet Localization Protocol

6.2. Localization Accuracy

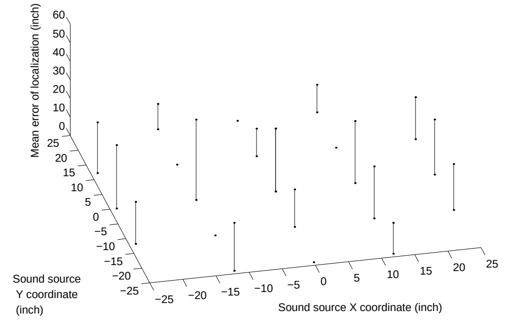
Since the purpose of proximity-based localization is to find the closest sensor, we define the following metric to measure localization error e:

$$e = \Big| d(p,S) - d(p,S^*) \Big|, \tag{1}$$

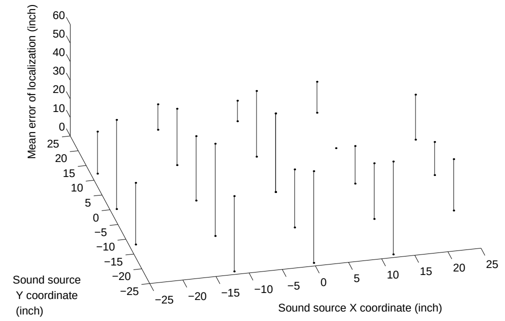
where p is the location of sound source. S is the location of elected sensor. S^* is the location of the sensor closest to p. $d(x,y)$ measures the Euclidean distance between x and y.

For each location of the sound source in Fig. 5(b), 10 trials of experiments are carried out using Lightning Protocol and DP protocol respectively. Furthermore, the DP protocol results are ideal in the sense that we only count those trials where no data packet loss occurs. Fig. 7 shows localization errors for both schemes.[4]

From Fig. 7, we see that Lightning Protocol achieves comparable or even better accuracy than ideal DP protocol. This is because DP protocol requires accurate clock synchronization to determine which sensor has the earliest TOA[5].



(a) Lightning Protocol



(b) Data Packet Localization Protocol

Figure 7. Localization Error Comparison

6.3. Election Delay

The election delay T_{elec}^{data} of DP protocol are determined by two factors, *i.e.*, (*i*) the medium access control protocol used and (*ii*) the order of transmissions for sensors. In TinyOS 1.0[2], a simple CSMA/CA mechanism with fixed contention window size cw is implemented. Upon detecting an idle channel, sensors that have backlogged packets first back-off randomly (uniformly distributed in $[0, cw]$) and then transmit if the channel remains idle. The current TinyOS implementation does not retransmit data packets in presence of collisions. We measure two delays in the DP protocol. The first one is T_{cs1st}^{data}, defined as the time for the closest sensor to send out its first data packet; the second quantity is T_{any1st}^{data} defined as the time it takes to send out the first data packet from any sensor. Clearly, $T_{cs1st}^{data} \geq T_{any1st}^{data}$. And T_{any1st}^{data} is the shortest possible election delay a data packet based scheme can achieve (even for schemes that favor the sensors with larger amplitude reading and let them transmit first[10]).

We measure the election delay of Lightning Protocol and compare it against the delays measured in DP pro-

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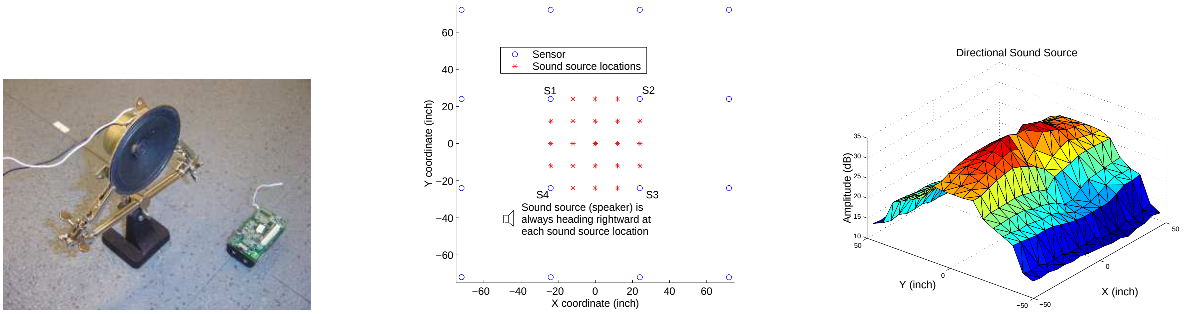
[4] Recall that for Lightning Protocol to run correctly, we require that the directionality of the sound source must be bounded, *i.e.* the closest sensor should always be able to recognize the beep no matter what direction it is oriented toward the sound source (see Section 3.2). However, the directionality of the sound source deployed in the experiment slightly exceeds this requirement, so that for a small percentage of trials, the closest sensor fails to recognize the beep. Instead, sensors slightly farther away overhear the beep and transmit RF bursts. This sometimes results in multiple sensors being elected. In this case, we count the winner farthest away from the sound source as the final elected sensor as a worst case estimation on localization error. Fortunately, even in such cases, the bursting sensors that are slightly farther away than the closest sensor still serve to suppress the majority of sensors so that both the localization error and the number of election winners are still low. We observe only a very small number of trials generate two winners; and no trial generates more than two winners. This is acceptable since in practice most applications are more concerned with localization error, which is already shown to be good in Fig. 7.

[5] In our implementation, clock synchronization is done by broadcasting a sync-packet from a dedicated synchronization node before each beep. Every sensor, on receiving the sync-packet resets its local clock to 0.



(a) Speaker (directional sound source) (b) Top-view of sensor layout, sound source (speaker) orientation and locations (c) Directional sound field of the speaker

Figure 5. Testbed Settings

tocol. This comparison errs on the pessimistic side for Lightning Protocol, as in DP protocol we don't carry out retransmission for collided packets.

	Max	Min	Mean
T_{elec}^{light} (ms) winner colored 4	13.7	13.4	13.6
T_{cs1st}^{data} (ms)	58.8	15.4	28.9
T_{any1st}^{data} (ms)	40.8	14.9	20.2

Table 2. Statistics of Election Delay

Fig. 8(a)(b)(c) show the measurement results of T_{elec}^{light}, T_{cs1st}^{data} and T_{any1st}^{data} respectively.[6] From Fig. 8(a), we see T_{elec}^{light} is fixed and is only determined by the color of the elected sensor; In Fig. 8(b) and (c), T_{cs1st}^{data} and T_{any1st}^{data} are scattered because of the random back-off mechanisms in TinyOS radio stack .

Table 2 compares statistics of T_{elec}^{light}, T_{cs1st}^{data} and T_{any1st}^{data}. Clearly, even the maximum T_{elec}^{light} (when elected sensor is colored 4) is shorter than the minimum T_{cs1st}^{data} and T_{any1st}^{data}. This indicates that Lightning Protocol always incurs less election delay than any data packet-based schemes.

6.4. Number of Transmissions

Next, we count the number of transmissions in the Lightning Protocol. The results are summarized in Table 3. From the analysis in Section 4.3, we know that in Lightning Protocol, at most 4 sensors would burst and each bursts only once, independent of the total number of sensors hearing the beep. This is corroborated by the experimental results. In Table 3, we see 81.4% of the localizations only involves *one* burst (broadcast).

Number of Bursts	1	2	> 2
% of Localization Trials	81.4%	18.6%	0

Table 3. Number of Bursts per Localization

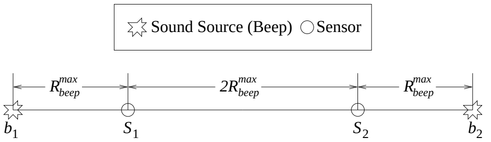


Figure 9. Sufficient spatial separation of two simultaneous beeps

6.5. Multiple Sound Events

Lightning Protocol can effectively handle multiple sound events (beeps) if the events are separated either temporally by at least $T_{bound}^{\star} + T_{reset}^{\star}$ units of time or spatially by at least 4 times the maximal acoustic audible range (*i.e.* $4R_{beep}^{max}$, where R_{beep}^{max} is the maximal audible radius from any sound source). The minimal spatial separation requirement is derived as follows (Fig. 9). Suppose beep b_1 and b_2 take place simultaneously, and b_1 and b_2 are $4R_{beep}^{max}$ apart from each other. The most remote sensors that can hear b_1 and b_2 are R_{beep}^{max} away from b_1 and b_2 (denoted asS_1 and S_2 in the Fig. 9 respectively). S_2's RF broadcast only needs to cover a radius of $2R_{beep}^{max}$ to reach all sensors that can hear b_2. Therefore, the broadcast of S_2 does not interfere with any sensor (say S_1) that can hear b_1, and vise versa.

Take our experiment testbed settings for example, we assume $R_{beep}^{max} = 15m$. this should translate to a separation of beeps by at least $91ms$ in time *or* by at least $60m$ in space.

7. Conclusion

In this paper, we exploit the application domain-invariant knowledge that acoustic waves propagate much slower than electromagnetic waves to devise

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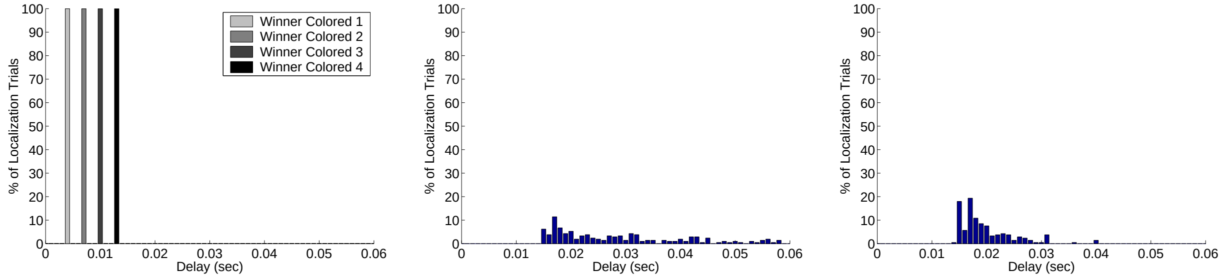
[6] The comparison is made between Basic Lightning Protocol and DP Protocol. Since both protocols share the same acoustic propagation delay from sound source to the closest sensor, and share the same TOA recognition module, time zero refers to the time that TOA is recognized at the closest sensor. For Energy-Efficient Lightning Protocol, there should be an additional Δ_{defer} delay. However, if the corresponding DP Protocol is also energy efficient, it should also have the additional Δ_{defer} delay.



(a) Lightning Protocol: Election delay distribution

(b) DP Protocol: Distribution of T^{data}_{cs1st} (time when the 1st packet is sent out from the closest sensor)

(c) DP Protocol: Distribution of T^{data}_{any1st} (time when the 1st packet is sent out from any sensor)

Figure 8. Election Delay Comparison

a new acoustic localization protocol called Lightning Protocol, which finds the closest sensor to the sound source in a network of regularly placed wireless sensors. Both theoretical analysis and experimental results are presented. Lighting Protocol is shown to have a very short and bounded delay ($O(1)$). It only incurs $O(1)$ wireless broadcasts and in 81.4% of our experimental trials only one wireless broadcast was incurred. The protocol does not involve wireless data packet communication, instead, it deploys RF bursts so that wireless broadcasts can overlap. This greatly simplifies the design of its wireless communication module making it fast and reliable. Moreover, the protocol has little computation and storage requirement; and does not need clock synchronization among distributed sensors. The accuracy of Lightning Protocol is comparable and often better than an ideal DP scheme. The protocol is energy-efficient in the sense that sensor nodes only turn on radio in an on-demand fashion in presence of acoustic events for a constant bounded time. Finally, we demonstrate through experiments that Lightning Protocol can handle directional sound sources with variable intensities.

Finally, a limitation of current work is the assumption of regular placement of sensors. This limits applications. We will extend our work to allow random placement of sensors. We also plan to investigate more effective methods to handle multiple sound sources.

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