Applying Lightning Protocol to Gunshot Localization

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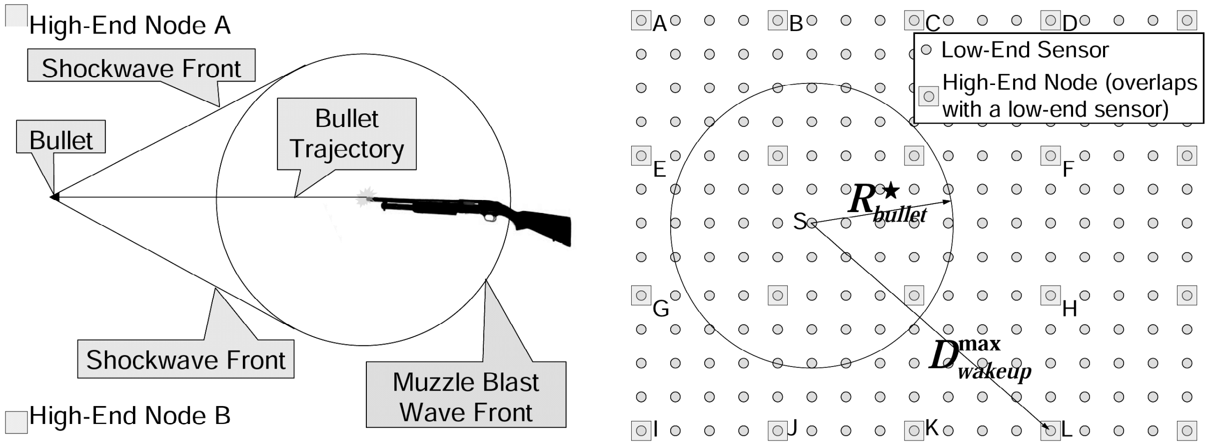
Lightning Protocol provides a deterministic ($O(1)$) and faster sensor election means for acoustic event localization, while incurs little extra cost. In fact, due to its simplicity, Lightning Protocol may even reduce the sensor's memory footprint, computation complexity and programming difficulty. This is always desirable. Just like having quick sort is desirable even though we already have bubble sort.

An example application can further demonstrate the usefulness of Lightning Protocol: waking up high-end gun-shot detection nodes. A gun-shot generates two sounds, one is bullet shockwave, generated by the supersonic bullet movement; the other is the muzzle blast, generated by gun powder explosion at the gun muzzle, and travels in sound speed. Mature high-end gun-shot detection systems, such as the series products of BBN counter-sniper systems [1][2][3], deploys high-end microphone arrays (refered to as *High-End Nodes* in the following)[1] to catch both bullet shockwave and muzzle blast. Specifically, the bullet shockwave front and its propagation direction must be detected by two high-end nodes on *both sides* of the bullet trajectory, as shown in Fig. 1(a). Later, the same high-end nodes need to catch the muzzle blast arrival. Based on the detected bullet shockwave (particularly its front *direction*), muzzle blast, and their arrival time difference, highly accurate estimation can be made on the location, azimuth angle, elevation angle, and caliber of the gun. These values are highly important for military or law-enforcement (anti-sniper) purposes[3].

Such high-end gun-shot detection nodes, however, are of high energy cost. For example, when the microphone array and localization modules are all turned on, the BBN Boomerange II system incurs a power consumption of 25watt [1]. In comparison, a MICA mote's power consumption is just 27 miliwatt



(a) Bullet Shockwave, Muzzle Blast and How High-End Nodes Localize a Gunshot

(b) Mixed Low-End Wireless Sensor and High-End Node Grids (using low-energy-cost low-end wireless sensors to wake up hibernating high-energy-cost high-end nodes before bullet shockwave hits them), Bullet's Uncertainty Circle, and High-End Nodes to Wake Up (those labeled A $\sim$ L)

Fig. 1. Gunshot Localization

[4] when fully turned on. It is hence much cheaper to let high-end nodes hibernate (turn off its microphone array and localization modules but keep RF listening; note compared to 25watt, the RF listening only costs 12miliwatt [4], which is ignorable for high-end nodes), while use (energy efficient) low-end wireless sensor grid to localize the muzzle blast and then wake up relevant high-end nodes before the bullet shockwave hits them. Note muzzle blast and bullet shockwave usually occupy non-overlapping acoustic frequency spectrum [2], therefore the low-end sensors' localization of muzzle blast is not interfered by the bullet shockwave.

When a low-end wireless sensor is elected, either by Lightning Protocol or DP Protocol, the current bullet location can be anywhere within radius

$$R^\star_{bullet} = v^{max}_{bullet} \times T^\star_{elec} + \frac{l}{\sqrt{2}} \tag{1}$$

from the elected sensor[1], where v^{max}_{bullet} is the bullet's maximum speed, l is the low-end sensor (square) grid edge length, v is sound speed, $T^\star_{bound}$ is election delay (the duration from gunshot till the nearest sensor is elected), and $\star$ can be either (energy efficient) Lightning Protocol or DP Protocol. That is, when a low-end sensor is elected, the current bullet location can be anywhere within a circle which centers at the elected sensor and has a radius of $R^\star_{bullet}$. We call this circle *Bullet's Uncertainty Circle*. What is more, the

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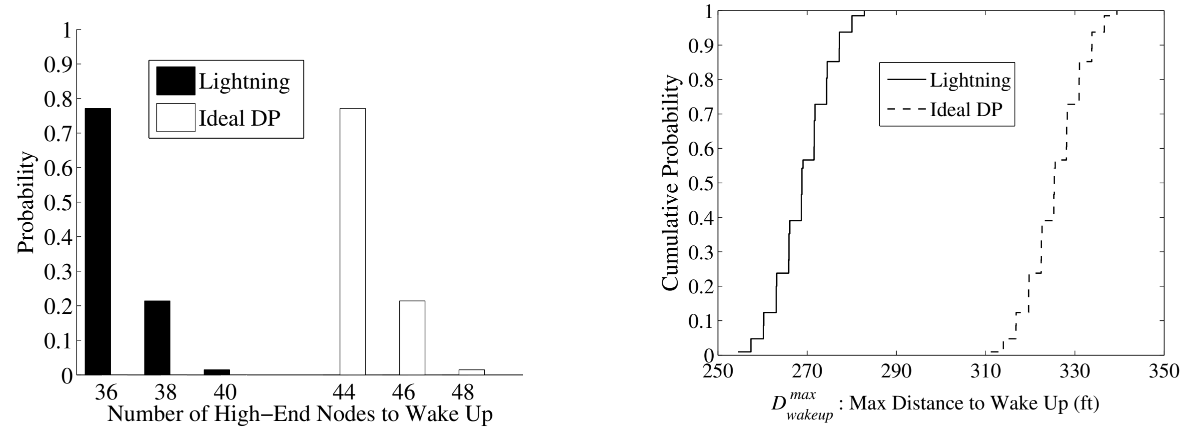
[1] To simplify the analysis, we assume both Lightning Protocol and DP Protocol always correctly elect the nearest low-end sensor. This also explains Equation (1)'s the last term ($l/\sqrt{2}$), which reflects the maximum distance from the elected sensor to the gun.

bullet's direction is unknown. Therefore, all high-end nodes that encloses the Bullet's Uncertainty Circle must wake up. For example, in Fig. 1(b), when sensor "S" is elected with the shown Bullet's Uncertainty Circle, it must immediately wake up all high-end nodes labeled "A" through "L". For convenience, we also denote the maximum distance between the elected sensor and any to-wake-up high-end node as D_{wakeup}^{max}. For Fig. 1(b), D_{wakeup}^{max} refers to the distance between "S" and "L".

Without loss of generality, we reasonably look at the case where the low-end sensor grid edge length $l = 4$ft, the high-end sensor grid edge length $L = 40$ft, $v_{bullet}^{max} = 4$ft/ms [5], and the gunshot can take place anywhere with uniform probability. The upper bound of Lightning Protocol election delay $T_{elec}^{lightning}$ can be calculated from Corollary 1 or 2 of [6]. This upper bound is $O(1)$ and is very small: approximately a packet preamble time, shorter than the time needed to transmit one packet. DP Protocol's election delay T_{elec}^{data}, however, is theoretically unbounded. To be overly optimistic on the DP Protocol side, we assume T_{elec}^{data} to be its *lower bound*: T_{any1st}^{data}. Remember for each election, $T_{any1st}^{data} \overset{def}{=} \min_{i \in \mathcal{S}}\{\tau_i\}$, where $\mathcal{S}$ is the set of all sensors ever transmit packets for the election, and τ_i represents the time cost from sensor i recognizes the beep till sensor i transmits its first data packet for the election. No matter how sophisticated the DP Protocol is, T_{elec}^{data} cannot be shorter than T_{any1st}^{data}. To be even more optimistic on the DP Protocol, we use the minimal measured T_{any1st}^{data} (14.9ms, see Table II of [6]) in the following comparison. Because $T_{elec}^{lightning}$ is shorter than T_{elec}^{data}, according to Equation (1), $R_{bullet}^{lightning}$ is much shorter than R_{bullet}^{data}, making the Bullet's Uncertainty Circle much smaller under Lightning Protocol, and therefore results in much less high-end nodes to wake up and much less D_{wakeup}^{max}. The quantitative anaysis results are shown in Fig. 2, which compares the probability distribution of D_{wakeup}^{max} and number of high-end nodes to wake up under Lightning Protocol and DP Protocol respectively.

Note, in Fig. 2, both Lightning Protocol and DP Protocol are energy efficient. That is, during idling time, low-end sensor only turns on acoustic sensing and turns off RF transceiver; when a beep is recognized, the sensor turns on RF receiving for $\Delta_{defer} = R_{beep}^{max}/v + \Delta_{recg}$, and only if it is not suppressed during the Δ_{defer} period will it switch to RF transmitting to join the election. Although a muzzle blast is very loud, by adjusting the decibel threshold for beep recognition, R_{beep}^{max} can still be adjusted. Specifically, the majority of muzzle blasts are of $150 \sim 160$dB, measured 3.3ft (1meter) from the muzzle [7][8]. In open space, the muzzle blast attenuates in square rate at least [9]. Therefore, at a distance of 33ft, a muzzle



(a) Probability Distribution of Number of High-End Nodes to Wake Up when a Low-End Sensor is Elected.

(b) Cumulative Distribution of D^{max}_{wakeup} when a Low-End Sensor is Elected.

Fig. 2. Comparison of D^{max}_{wakeup} and number of High-End Nodes to wake up between Lightning Protocol and DP Protocol, suppose gunshot takes place at any location with uniform probability.

blast is reduced by no less than $10\log_{10}(33/3.3)^2 = 20(\text{dB})$, reaching a sound level of $130 \sim 140\text{dB}$ or below. By picking a proper decibel threshold, such as 145dB, we can make the muzzle blast undetectable from farther than 33ft away, i.e., we can make $R^{max}_{beep} = 33\text{ft}$.

According to Fig. 2(b), under Lightning Protocol, the upper bound of D^{max}_{wakeup} is 282.8ft. Note the maximum RF range of IEEE 802.11 or IEEE 802.15.4/ZigBee is 328ft (100meter). Therefore, under Lightning Protocol, the elected sensor can wake up its high-end nodes right after it enters elected mode with one RF broadcast (all other sensors are suppressed at the time, causing no MAC contension). Furthermore, because the upper bound of $R^{lightning}_{bullet}$ can be calculated offline, the broadcast only needs to contain the elected sensor's coordinates. A high-end node can calculate its distance to the elected sensor, compare it with $R^{lightning}_{bullet}$, and determine whether or not it should wake up. While for DP Protocol, there are 43.4% probability that D^{max}_{wakeup} exceeds 328ft (100meter). In such cases, multi-hop RF broadcast is needed. The delay caused by multi-hop communication will further increase the D^{max}_{wakeup} and the number of high-end nodes to wake up, making the situation even more difficult for DP Protocol.

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