TIME DOMAIN®

PulsON® RangeNet / ALOHA Guide to Optimal Performance

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Introduction

RangeNet implements a wireless Media Access Control (MAC) Network layer on top of the RCM link layer in PulsON radios, relieving users from coordinating airtime when initiating packets directly to the RCM link layer. A high-level illustration of the embedded radio network layers is provided in **Figure 1**.

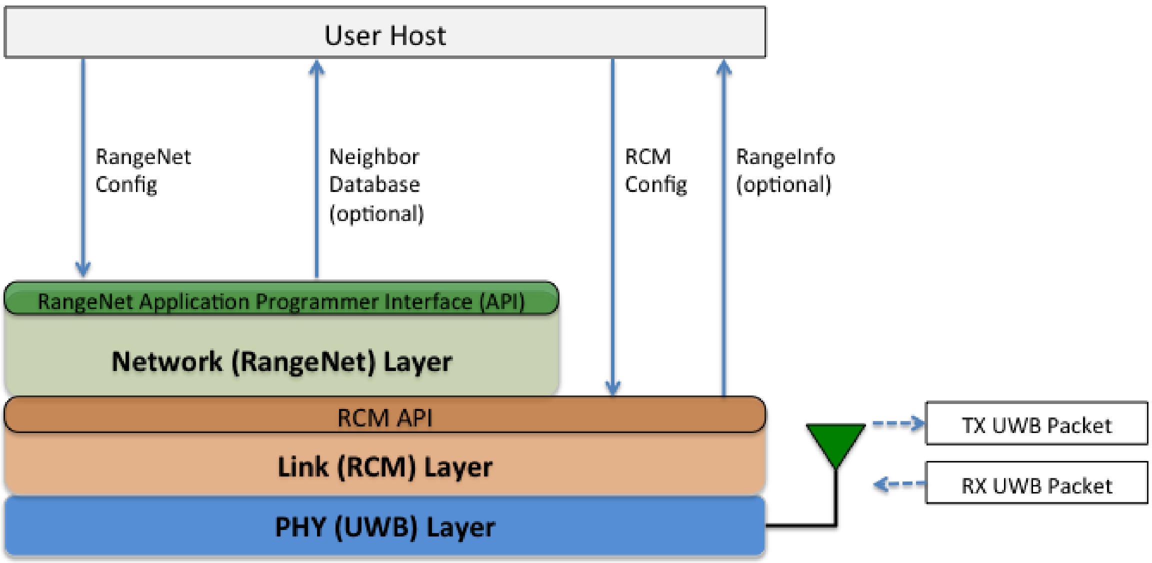

Fig. 1: Embedded network layers available in PulsON radios

RangeNet implements two sub-modes of operation: ALOHA and TDMA (Time Division Multiple Access.) Pure "ALOHA" is one of oldest and simplest wireless time division techniques (http://en.wikipedia.org/wiki/ALOHAnet). It provides random scheduling without centralized control or timing. This "pure ALOHA" mode is particularly advantageous for Mobile Ad-Hoc Network (MANET) applications, node discovery in mixed-mode networks, and for quick multi-responder performance evaluation. Pure ALOHA rather than slotted ALOHA was implemented due to pulsed UWB's inherent advantage in "Capture Effect" (http://en.wikipedia.org/wiki/Capture_effect) for higher efficiency than narrowband radio signaling (reference one of the ION papers which proves this.)

This paper particularly addresses the operation and performance testing of the Automatic Congestion Control (ACC) component of RangeNet/ALOHA. When ACC is enabled the radios automatically adjust transmission rate based on sensed network size in order to optimize ranging throughput. In certain cases integrators may benefit from bypassing ACC and manually configuring the random scheduler with constant ranging rates.

Theory of Operation and Nomenclature

Fundamentally each node in a PulsON network must manage two things:

1. When to transmit a request packet
2. Which neighboring node to target for a Two-Way Time-of-Flight (TW TOF) distance measurement

As an example, consider the network of six nodes labeled A through F depicted in **Figure 2**. In the illustration Node A transmits a Range Request Packet with Node B as its target. Node B responds at a precise time in support of the embedded PulsON TW-TOF protocol with a Range Response Packet. The complete interaction is denoted as a single "Ranging Conversation." Node A, after acquiring Node B's response calculates the distance AB and reports this measurement, along with numerous other metrics, to a co-located host.

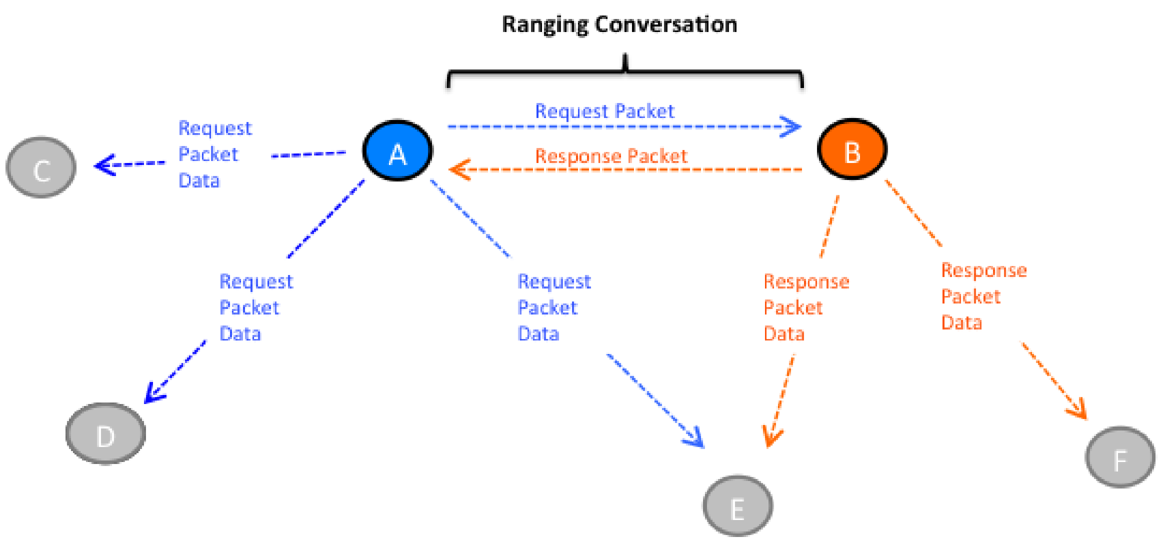

Fig. 2: A single range conversation initiated by "requester" A, targeting "responder" B

Note all the nodes in Node A's "Network Neighborhood" (B, C, D, and E) overhear node A's Request Packet and demodulate any user data in Node A's Request Packet (as well as accompanying metrics such as direct path signal strength.) Likewise, all nodes in Node B's neighborhood (A, E, and F) overhear node B's Response Packet data and signal metrics.

By design randomize ALOHA networks allow for a certain proportion of collisions, which can cause dropped packets. Unlike narrowband radios, UWB signaling supports a significant amount of simultaneity. For instance nodes E and F could separately complete a range measurement at the same time AB is being measured. Typically when a single node is the target of multiple range requests the closest requester (with the strongest signal) wins.

The basic approach to optimizing RangeNet/ALOHA performance is maximizing node transmission rates to the point of the maximum rate of *successful* range conversations. It is important to distinguish between a node's *Offering Rate*, *Ro*, and its *Success Rate*, *Rs*. Although *Rs* is the metric we want to maximize, each node's firmware only has direct control over *Ro*. The goal is to have all nodes control *Ro* until *Rs* is maximized, while also allowing enough spare time to allow new nodes to enter the network.

The relationship between *Ro* and *Rs* for PulsON UWB ranging conversations was determined through theoretical analysis, simulation, and testing. However this relationship changes with the *network size*, *N*, and the *conversation duration T*. *T* varies with the pulse integration index configured. An *Airtime Density Equation* is established to normalize these factors across N and T.

Relating Ro and Rs

Through simulation and testing an optimal airtime density K_{opt} was determined that maximizes the rate of successful range conversations Rs based on the configured offering rate Ro. An example of the test results used to verify Kopt is provided in **Figure 3**.

Consider the lowest line in **Figure 3**, generated with 9 nodes in the network as the offer rate Ro was increased from 1Hz to 15Hz. Two observations are apparent. First, at low offer rate, the success rate increases proportionally to the offer rate. At low airtime density most range conversations succeed. Second, as the offer rate increases, collisions cause the offer rate to flatten out to a maximum level, in the case of the 9 node network the maximum success rate occurs at approximately 3.3Hz. Thus for a 9 node homogenous network (all nodes take turns ranging to all other nodes) the success rate is limited to 3.3Hz.

For this network configuration the optimal Ro would maximize Rs while allowing sufficient opportunity for new nodes to join the network. Thus the point of 90% success (circled) was chosen as the control point, indicating a control point of Ro = 8Hz will provide optimal throughput for this network configuration.

Note for unimproved narrowband networks collisions cause a distinct decrease as the offer rate increases past this optimal point. UWB natively provides a high capture effect, which allows continued success of closer/stronger links nodes at the expense of longer/weaker links.

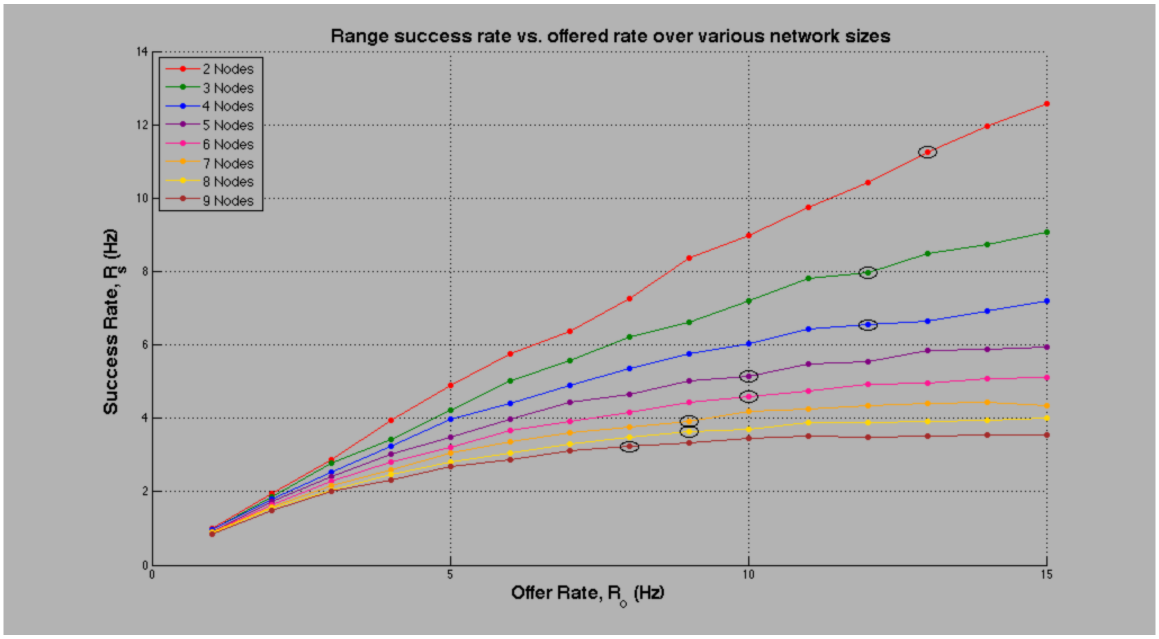

Fig. 3: The success rate, Rs, as Ro increases from 1 to 15 Hz. Each line represents a different network size, N, from 2 to 9 nodes. In this test all nodes are configured at PII7 (T=0.022s) and implement "Round Robin" targeting.

The Airtime Density Equation

In theory (confirmed through experimentation) there exists an optimum "airtime density" which supports this optimal relationship between Ro and Rs. This airtime density which maximizes success rate is denoted as Kopt and relates to N, Ro, and T by

$$K_{opt} = N * R_o * T \tag{1}$$

where:

K_{opt} is the optimal airtime density,
N is the number of nodes within communication range,
R_o is the mean *rate* of range requests.
T is the time consumed by one complete range conversation.

Through tests across many network configurations Kopt = 0.4 was determined to maintain optimal throughput. Thus maintaining airtime density of about 40% maximizes success rate for PulsON ranging networks.

Kopt is assumed constant. If the number of nodes N increases then, in order to maintain optimal performance, either Ro or T must decrease. For PulsON networks, T, the range conversation duration, is hardcoded based on the selection of Pulse Integration Index (PII). Thus ACC in each node senses N, the number of neighbors in its vicinity, and manipulates Ro accordingly.

The Effective Network Size, Neff

For a homogenous ranging network, where all nodes range to each other in a round-robin fashion, the number of active Links, L, is a straightforward function of the number of nodes in the network

$$L = N(N\text{-}1) \qquad (2)$$

RangeNet supports a variety of non-homogenous configurations. For instance nodes can be configured as "beacons", which never initiate range requests (they only respond.) Also exclusion lists, configured in each node, prevent that node from targeting any node in the list for range requests. Both these configuration options reduce the number of active links required for network support, allowing increased Ro to maintain optimal airtime density.

In these non-homogenous configurations the *effective* network size, Neff, is determined from the total number of active Links, L, which must be supported

$$N_{eff} = \frac{1}{2}\left(1 + \sqrt{4L+1}\right) \qquad (3)$$

For example given a network of 3 mobile (non-beacon) nodes (M) and 6 beacon nodes (B), where the mobile nodes are excluded from ranging to each other the number of active links is computed

$$L = M*B = 3*6 = 18 \qquad (4)$$

Once L is computed equation 3 can be used to compute Neff = 4.8. So, in this example, although there is a total of 9 nodes in the network, optimal airtime would consider the *effective network size* as just under five. The revised Airtime Density Equation used by ACC is

$$K_{opt} = N_{eff} * R_o * T \qquad (5)$$

where Neff is calculated using equation 3.

Controlling Ro

The ALOHA scheduler transmits range requests at an average rate Ro based on a discrete uniform random delay between range attempts. The delay interval is configured by specifying Minimum Time Between Transmissions (*minTBT*) and the Maximum Time Between Transmissions (*maxTBT*.) The Average, or Mean Time Between Transmissions is simply

$$meanTBT = (minTBT + maxTBT)/2 \qquad (6)$$

Since the mean rate is the inverse of the mean delay

$$R_o = 2/(minTBT + maxTBT) \tag{7}$$

where minTBT and maxTBT are the configurable parameters.

Random throughput is maximized when the uniform delay interval is maximum for a given mean. This implies minTBT should be minimized and maxTBT adjusted based on a given Ro.

However a minTBT of zero is a bad choice. The scheduling event triggers at the beginning of each request packet transmission. If the RangeNet layer attempts to transmit a new packet while the RCM link layer is busy completing a ranging conversation its previous packet the transmit opportunity will be lost. Therefore the minimum good choice for minTBT is T, the conversation duration.

$$minTBT = T \tag{8}$$

where T is dictated by the configured PII. For instance PII=7 dictates the ranging conversation takes 0.022 seconds to complete.

Thus ACC manages Ro by controlling *maxTBT* using

$$R_o = 2/(T + maxTBT) \tag{9}$$

The Congestion Control Algorithm

First, the internal Neighbor Database is queried to calculate the total number of active Links, L to support. This value is used to calculate Neff as in equation 3

$$N_{eff} = \tfrac{1}{2}\left(1 + \sqrt{4L + 1}\right) \tag{10}$$

Next the Airtime Density equation is manipulated to compute Ro as a function of Neff

$$R_o = {}^{K_{opt}}\!/_{N_{eff}T} \tag{11}$$

where $K_{opt} = 0.4$ is currently hard-coded in the firmware.

Finally, this derived Ro is used to calculate maxTBT through an inverse form of equation 9

$$maxTBT = {}^{2}\!/_{R_o} - T \tag{12}$$

In fact, the entire algorithm can be combined algebraically into a single working equation producing maxTBT as a function of T and Kopt:

$$maxTBT = T\left(\frac{1+\sqrt{4L+1}}{K_{opt}} - 1\right) \tag{12}$$

Example

Reconsider the previous example navigation network supporting six reference “beacons” which only respond to mobile requests. Three mobiles repeatedly range to all six beacons, but are excluded from ranging to each other. PII=7 implying T=0.021s.

```
T =  ConversationTime(7)
L = 3*6;
N = 0.5*(1+sqrt(4*L+1));
Kopt = 0.40;

maxTBT = T*(2*N/Kopt-1)
minTBT = T;
meanTBT = (maxTBT+minTBT)/2;
R = 1/meanTBT;

fprintf('T:%3.3fs, L:%d, N:%3.1f, Kopt:%0.3f, maxT=%3.3fs, minT=%3.3fs,
meanT=%3.3fs, R=%3.3fHz\n', ...
  T, L, N, Kopt, maxTBR, minTBR, meanTBR, R);
```

Output:

```
T =
    0.0213

maxTBT =
    0.4863

T:0.021s, L:18, N:4.8, Kopt:0.400,
maxT=0.486s, minT=0.021s, meanT=0.254s, R=3.940Hz
```