Therefore, the delays taking place between any pair of intermediate nodes are considered to be similar in this paper, which can be estimated simply by $T_{\text{hop}} = T_q + T_p + T_{\text{tx}}$. Consequently, the delay between current node to the sink node is proportional to the hop count between the two nodes.

2) The End-to-end Energy Consumption: Given a constant packet size and a fixed propagation distance, we consider every sensor node will consume the same energy to forward the packet. Therefore the end-to-end energy consumption for delivering a data packet from the source node to the sink node is proportional to the number of transmissions, i.e., the hop count. The basic energy model of one hop transmission in this paper is:

$$E_{\text{hop}} = C \cdot D_{\text{hop}}^\alpha$$

where $C$ is a constant value, $D_{\text{hop}}$ is the transmission distance, and the parameter $\alpha$ is the path loss exponent, depending on the environment, typically is equal to 2 when free space propagation is assumed. For the sake of simplicity, $C$ is set to 1, and $\alpha$ is set to 2. Then, $E_{\text{hop}} = D_{\text{hop}}^2$. Let $H_{s\rightarrow t}$ be the hop count from the source node to the sink node. Then, the end-to-end energy consumption can be estimated by:

$$E_{\text{ete}} = \sum_{i=1}^{H_{s\rightarrow t}} E_{\text{hop}}(i)$$
$$= E_{\text{hop}} \cdot H_{s\rightarrow t}$$
$$= D_{\text{hop}}^2 \cdot H_{s\rightarrow t}$$

which increases linearly with the value of $D_{\text{hop}}$. Motivated by an interesting feature that some sensor devices can transmit at different power levels [27], this paper assume that the sensor node has the capability of power control to reduce end-to-end energy consumption.

3) Energy-Delay Tradeoff: Typically, a geographic routing mechanism (e.g., GPSR [19]) intends to maximize packet progress at each hop in a greedy fashion. Since such a distance-based scheme introduces nearly maximal hop distance, the end-to-end delay could be minimized while more energy will be consumed based on our energy model.

However, achieving minimum delay is not beneficial for some delay sensitive applications when the minimum delay is smaller than the application specific QoS delay boundary (i.e., $T_{\text{QoS}}$). In the case that the earlier arrival of a data packets is not necessary, an intermediate sensor node can reduce the transmission power with a smaller transmission range for delivering packet to next hop in order to reduce energy consumption, but not too small to still be able to guarantee the delay objective.

- Propagation delay: This parameter can be neglected when compared to the other delays.
- Transmission delay: We assume that the size of a data packet does not change between a source-sink pair, its transmission delay (denoted by $T_{\text{tx}}$) remains constant between any pair of intermediate sensor nodes.

Fig. 3. Illustration of the Strategic Location Selection in MGR scheme.

B. End-to-end Delay Objective

Let $D_s^t$ denote the distance between source and sink. Let $R_{\text{max}}$ denote the maximum transmission range of a sensor node. Then, the minimum end-to-end delay is equal to $T_{\text{min}} = \frac{D_s^t}{R_{\text{max}}}$, which is realized by the use of the shortest path with maximum progress at each hop. Then, for a certain network topology, an multimedia application is allowed to adjust application-specific end-to-end delay $T_{\text{QoS}}$ subject to the following constraint at least: $T_{\text{QoS}} > T_{\text{min}}$, otherwise the QoS delay cannot be achieved.

C. Calculating the Desired Hop Distance at Current Node

Let $t_{s\rightarrow h}$ denote data packet’s experienced delay up to current node. Let $t_{\text{current}}$ denote the current time when the routing decision is being made; let $t_{\text{create}}$ denote the time when the packet is created at the source node. Then, $t_{s\rightarrow h}$ can be easily calculated by the difference between $t_{\text{current}}$ and $t_{\text{create}}$. Then, the reserved time credit for the data delivery from current node to the sink node, $T_{h\rightarrow t}$, can be calculated by:

$$T_{h\rightarrow t} = T_{\text{QoS}} - t_{s\rightarrow h}$$

Based on $T_{h\rightarrow t}$ and $T_{\text{hop}}$, the desired hop count from current node to the sink node can be estimated as

$$H_{h\rightarrow t} = \frac{T_{h\rightarrow t}}{T_{\text{hop}}}$$

Upon the reception of data packet from its previous hop, the current node will know the position of the sink node. Then, distance from current node to the sink node, $D_{h\rightarrow t}$, can be calculated according to the positions of itself and the sink node. Let $D_{\text{hop}}$ denote the desired hop distance for next-hop-selection. Then,

$$D_{\text{hop}} = \frac{D_{h\rightarrow t}}{H_{h\rightarrow t}}$$

D. Strategic Location for Next-hop-selection

In this paper, strategic location means the ideal location of current node’s next hop. Based on $D_{\text{hop}}$ calculated in Section V-C, the strategic location of MGR is decided as in Fig. 3.