# A CONNECTIONLESS APPROACH TO LARGE SCALE SENSOR NETWORKS

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## ABSTRACT

*We consider a connectionless approach to large scale sensor network. Given a fixed traffic load and fading characteristics, analytical expressions for energy consumption are derived for two types of network architectures: the flat ad hoc sensor network and sensor network with mobile access. We investigate the energy scaling behavior for both data-centric and location-centric applications.*

## 1. INTRODUCTION

### 1.1. Connectionless Networking

The idea of connectionless networking, as pointed out in [1], "is the capability of having information move between network elements without a preconceived path between source and destination." By not having to maintain connections at both physical and network layers, for applications with low traffic load, significant reduction of energy consumption can be expected. This is one of the reasons that motivates the DARPA connectionless program [2] that aims at developing "technology to allow radio networks to send and receive messages without any initial link acquisition, or any previous sharing of routing information. This will, in turn, improve energy per bit of delivered information by as much as 100 - 1000 times."

Connectionless networking can be viewed, perhaps, as a reactive approach to networking. By this we mean not only a reactive networking layer but also a reactive physical layer, where each node shuts down most of its circuitry and initiates connections only when there is a message to transmit. In contrast, a proactive physical layer will maintain the synchronization and update channel state information, ready to transmit whenever there is a message.

To a large extent, whether to have a proactive or a reactive physical layer has not been considered an important factor in the literature. Indeed, if the design metric is to maximize the throughput or minimize the delay, the physical layer strategy, proactive or reactive, will have a minimum impact. If the objective is to minimize energy consumption, however, there is a difference between the two physical layers, and such a difference is especially significant when waking up a node and bringing it to the ready state of transmission can consume considerable amount of energy. It is apparent that there is a tradeoff between proactive and reactive physical layers as a function of the message duty cycle.

### 1.2. Connectionless Approach to Sensor Networks

Energy consumption is a dominant factor in the design of large scale sensor networks, which makes a connectionless approach appropriate. Sensor networks are application specific, and it is necessary that network architecture is part of the design consideration. One type of sensor network is based on the architecture of ad hoc networking in which sensors communicate with each other and route information toward gateway nodes [11]. An alternative scheme is sensor network with mobile access (SENMA) [3–5]—a hierarchical architecture for low power and large scale sensor networks was proposed.

As shown in Figure 1, SENMA has two types of nodes: sensors and mobile Access Points (APs). Sensors in SENMA are low cost nodes with limited processing and communication capability. They are deployed randomly in large quantity. For some applications such as radio frequency tags, sensors may even be passive. The primary function of sensors are data collection, local processing, and delivering data to mobile APs. The mobile APs, in contrast, are powerful nodes both in their communication and processing capability and in their ability to traverse the network. Ex-

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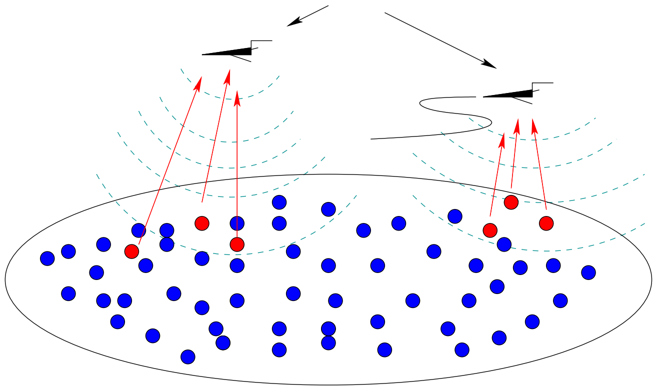

**Fig. 1**: Sensor Networks with Mobile Access

amples are manned/unmanned aerial vehicles, ground vehicles equipped with power generators, or specially designed light nodes that can hop around in the network. Access points retrieve the data from sensors, and deliver it to a remote control center (possibly via a satellite link). They may form a small ad hoc network and perform collaborative data collection and post processing, adding a new dimension in the space-time domain. Access points need not always be present or operational along with the sensors; they may be called upon for data collection, or they may be embedded in the network, staying passive until called.

One can view SENMA as an "inversion" of the cellular architecture: mobile users in cellular network correspond to stationary sensors in SENMA, stationary base stations the mobile APs. In both architectures, the network has two types of nodes with the smaller number of powerful nodes taking the responsibility of network operations. Such a division of network function is crucial to the scalability with respect to the number of end-nodes: phones in the cellular network and sensors in SENMA.

The presence of mobile APs makes SENMA a suitable candidate for connectionless networking: sensors communicate with mobile access points directly, delivering information to and receiving instructions from mobile access points. If data need to be transported from one part of the network to the other, mobile APs can serve as relaying nodes. In a way, the network is connected through mobile APs, and the connection is setup only when necessary.

The fundamental idea behind connectionless networking over the SENMA architecture is to shift network functions, as much as possible, away from the sensor nodes to mobile access points that are not energy and bandwidth constrained. The combination of direct sensor-mobile access points transmission and the down link broadcast from mobile access points to the sensor network can be used effectively for such purposes. For example, at the physical layer, timing recovery and synchronization among sensors can be simplified by the presence of strong beacon signals transmitted by the mobile APs. For some applications, sensors need to know their own locations. This, too, can be facilitated by the mobile AP. The medium access control (MAC) layer of SENMA is also simplified; the MAC becomes a many-to-one communication problem, allowing the use of a number of energy efficient distributed schemes [5–7]. In SENMA, routing packets from one part of the network to another, if needed, is carried out by mobile APs, which will not be considered in this paper.

### 1.3. Summary of Results and Organization

In this paper, we take a theoretical approach to analyzing energy consumption of SENMA as compared with the prevailing architecture — multihop ad hoc structure (see Figure 2) where sensors propagate data in multihops toward the gateway node at the center of the network. We are particularlly interested in the following questions: how the energy consumption scales with the number of sensor nodes, by increasing either the node density or the geographic size of the network? which network operation, message transmission or reception, dominates the total energy consumption. Such questions, while possible to be tackled via simulations, are more suitable for an analytical approach.

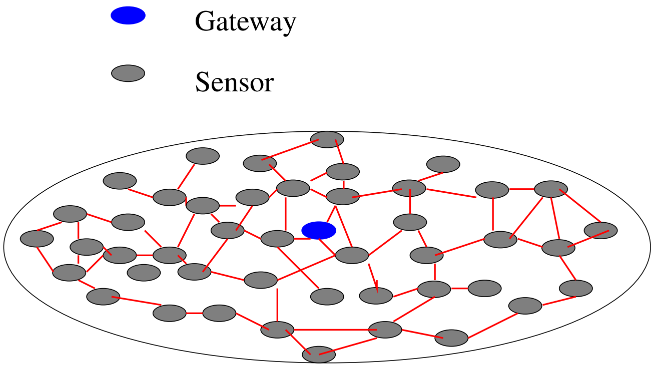

**Fig. 2**: Multihop ad hoc sensor networks with gateway nodes.

We begin with specifications of the network and radio models in Section 2. We then present basic elements in our energy analysis. Energy efficiency of ad hoc and SENMA architectures for data-centric and location-centric applications are analyzed in Section 4 and 5, respectively.

### 1.4. Related Work

The SENMA architecture is discussed in [3,4]. The medium access control in SENMA is considered in [5–10]. Most of the literature on sensor networks focuses on the multihop architecture (see [11] for a survey). In [12], an extension of the multihop architecture with mobile sensors is considered, and a specific MAC protocol—Eavesdrop-And-Register—is introduced that integrates mobile nodes into the network. Nonetheless, the primary network functions in [12] are not handled by the mobile nodes. In [13], the idea of using mobile nodes for message ferry is considered, where the objective is to use mobiles to provide non-random proactive routes. Bansal and Liu considered the addition of mobile nodes to relay packets [14].

The energy efficiency comparison between SENMA and the ad hoc architecture is first presented in [3] although the calculation there does not take into account the possibility of scaling the transmission radius according to the size of the network. The difference between previous analyses on energy consumption [15–17] and ours is that we explicitly account for both transmission and reception energies. The physical basis of our model comes from [18], where energy consumption is characterized at the circuit level, and it is stated that the transceiver consumes 2-3 times more power in receiving than in transmitting.

## 2. PROBLEM STATEMENT

### 2.1. Network and Radio Model

We consider a network with $N$ sensor nodes randomly distributed in a disk of radius $R$. Nodes are half duplex and capable of adjusting the transmission power to cover a neighborhood of radius $r$.

Nodes, when there is no on-going communication, are in the sleep state by turning off its transceiver. We assume that a node in the sleep state can be waken up by RF signals, which can be achieved by equipping each node with either an energy detector or a device called remotely activated switch (RAS) [19,20] enabled by the technology of RF tags. When the RAS receives a correct paging sequence, it turns on the transceiver and brings the node to the active state. In our analysis, we assume that each node has a unique paging sequence which can be a predetermined function of its ID. Note that when nodes are waken up by an energy detector, nodes can not be waken up individually; all nodes within the transmission range $r$ of the transmitting node will be waken up. In the calculation of energy efficiency, we ignore the energy consumed in the sleep state and energy consumed by the RAS and energy detector. It is, however, straightforward to incorporate them into our analysis.

When a node is actively receiving, it consumes $E_{\text{rx}}$ Joule per bit; The transmission of the node that covers a neighborhood of radius $r$ consumes $E_{\text{tx}}(r)$ Joule/bit which is given by [18,21],

$$E_{\text{tx}}(r) = e_{\text{tx}} + \max\{e_{\text{min}}, e_{\text{out}}r^{\alpha}\} \tag{1}$$

where $e_{\text{tx}}$ is the energy consumed by the transmission circuitry, $e_{\text{out}}$ the antenna output energy to reach, with an acceptable SNR, the destination unit distance away, and $e_{\text{min}}$ J/bit the minimum energy radiated regardless of the transmission range. Note that $e_{\text{min}}$ imposes a hard limit on the minimum transmission range:

$$r \geq r_0 \overset{\Delta}{=} (\frac{e_{\text{min}}}{e_{\text{out}}})^{\frac{1}{\alpha}}. \tag{2}$$

### 2.2. Application Specifications

Sensor networks are application specific, thus the specification of application domain is necessary. To this end, we consider query-reply operations where specific type of data are requested and gathered. In particular, we are interested in two different types of queries: (i) data-centric query and (ii) location-centric query. Data-centric query means that specific type of data (not necessarily the origin of the data) are requested. For example, it may be desirable to collect from those nodes who have measurements with certain characteristics (*e.g.,*temperature measurements higher than $100^oF$). In such cases, the access point (gateway node or mobile access point) does not know the locations where the requested data reside thus must flood the request throughout the network. For location-centric query, in contrast, the access point collects data from specific locations therefore knows the general location where the data reside. An example is the retrieval of data from any sensor located in a small geographic area.

## 3. BASIC ELEMENTS OF ENERGY ANALYSIS

In this section, we present basic elements upon which the network level energy analysis for ad hoc architecture is built.

### 3.1. The Minimum Transmission Range

In our energy analysis, the transmission range $r$ is optimized for energy efficiency. We first characterize the interval from which $r$ can assume values.

The first constraint on $r$ is the hardware limit given in (2). The second constraint is network connectivity, *i.e.,* $r$ should be large enough that the network is connected with high probability. Let $r_c(N)$ denote the minimum transmission range to ensure connectivity with probability 1 for a network with $N$ uniformly distributed node, we have, from

[22],

$$r \geq r_c(N) \overset{N\to\infty}{\to} R\sqrt{\frac{\log N}{N}} = \begin{cases} \mathcal{O}(\sqrt{\frac{\log N}{N}}) & \rho \uparrow \\ \mathcal{O}(\sqrt{\log N}) & R \uparrow \end{cases} . \tag{3}$$

We see that when the network size $N$ is increased by increasing the node density $\rho$, the minimum transmission range $r_c(N)$ eventually goes to $0$. If, however, $N$ is increased by increasing the geographic size $R$, the transmission range has to grow to infinity with rate $\sqrt{\log N}$ to ensure network connectivity.

Combining (2) and (3), we obtain the minimum transmission range $r_{\text{min}}$ as

$$r \geq r_{\text{min}} \stackrel{\Delta}{=} \max\{r_0, R\sqrt{\frac{\log N}{N}}\}. \tag{4}$$

The minimum number of neighbors of a node is thus given by

$$N_r(r_{\text{min}}) = \frac{r_{\text{min}}^2}{R^2}(N-1) = \begin{cases} \mathcal{O}(\log N) & \rho \uparrow, r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow, r_0 > 0 \\ \mathcal{O}(\log N) & R \uparrow \end{cases} . \tag{5}$$

### 3.2. One Hop Transmission

We now analyze the energy consumed in one hop transmission where a node $A$ transmits to one of its neighbors, say $B$. The energy consumption of this network operation depends on the waken-up scheme. First, consider that each node has a paging device that can wake up individual nodes. In this case, the energy consumed in one hop transmission includes the transmitting energy of $A$ and the receiving energy of $B$, *i.e.,*

$$\begin{aligned} \mathcal{E}_1 &= \min_{r \geq r_{\text{min}}} \; (E_{\text{tx}}(r) + E_{\text{rx}}) \\ &= \min_{r \geq r_{\text{min}}} \; (e_{\text{tx}} + e_{\text{out}} r^{\alpha} + E_{\text{rx}}) \\ &= \begin{cases} \mathcal{O}((\sqrt{\frac{\log N}{N}})^{\alpha}) & \rho \uparrow, r_0 = 0 \\ \mathcal{O}(1) & \rho \uparrow, r_0 > 0 \\ \mathcal{O}(\sqrt{(\log N)^{\alpha}}) & R \uparrow \end{cases} \cdot \end{aligned} \tag{6}$$

In all cases, the optimal transmission range for minimizing the on-hop energy consumption is $r_{\text{min}}$ given in (4).

If, on the other hand, a transmission wakes up all the neighbors of the transmitting nodes, we have

$$\begin{aligned} \mathcal{E}_1 &= \min_{r \geq r_{\text{min}}} \; (E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) \\ &= \min_{r \geq r_{\text{min}}} \; (e_{\text{tx}} + e_{\text{out}} r^{\alpha} + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) && (7) \\ &= \begin{cases} \mathcal{O}(\log N) & \rho \uparrow, r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow, r_0 > 0 \\ \mathcal{O}(\sqrt{(\log N)^{\alpha}}) & R \uparrow \end{cases} . && (8) \end{aligned}$$

Similar to the case with perfect waken-up scheme, the optimal transmission range for minimizing the on-hop energy consumption is $r_{\text{min}}$ given in (4).

From (4) and (7), we see that when $\rho$ increases, the energy consumed in listening dominates; perfect waken-up scheme (see (6)) leads to significant energy reduction in large networks. When $R$ increases, however, the energy consumed in transmission dominates; the perfect waken-up scheme does not change the scaling behavior of the energy consumption.

### 3.3. Point-To-Point Transmission

We now consider the multi-hop communication between two randomly chosen nodes $A$ and $B$. Let $h(x, r)$ denote the number of hops from $A$ to $B$ given that the distance between them is $x$ and the transmission range is $r$. It can be shown that when $N$ increases by increasing either $\rho$ or $R$, we have

$$h(x, r) \overset{N\to\infty}{\to} \frac{x}{r}. \tag{9}$$

Consider first the perfect wake-up scheme. Using the one-hop energy consumption given in (6), we obtain

$$\begin{aligned} \mathcal{E} &= \min_{r \geq r_{\text{min}}} \int_0^{2R} \mathcal{E}_1(r) h(x, r) p(x) \mathrm{d}x \\ &= \min_{r \geq r_{\text{min}}} \; (E_{\text{tx}}(r) + E_{\text{rx}}) \frac{\bar{x}}{r} \\ &= \begin{cases} \mathcal{O}(1) & \rho \uparrow \\ \mathcal{O}(\sqrt{N(\log N)^{\alpha-1}}) & R \uparrow \end{cases} \end{aligned}$$

For the case where all neighbors listen to the transmission, we have,

$$\begin{aligned} \mathcal{E}_{\text{s}} &= \min_{r \geq r_{\text{min}}} \int_0^{2R} \mathcal{E}_1(r) h(x, r) p(x) \mathrm{d}x \\ &= \min_{r \geq r_{\text{min}}} \; (E_{\text{tx}}(r) + (\frac{r^2}{R^2}(N-1))E_{\text{rx}}) \frac{\bar{x}}{r} \\ &= \begin{cases} \mathcal{O}(\sqrt{N \log N}) & \rho \uparrow, r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow, r_0 > 0 \\ \mathcal{O}(\sqrt{N(\log N)^{\alpha-1}}) & R \uparrow \end{cases} \end{aligned}$$

In all cases, the optimal transmission range is given by $r_{\text{min}}$. Again, we see that perfect waken-up scheme results in significant energy reduction when $\rho$ increases but the same scaling behavior when $R$ increases.

### 3.4. Flooding

We now consider the operation where one senor node (or the gateway node) floods a message over the whole network. Specifically, every node, upon receiving this message for the first time, transmits the message to all the neighbors. We thus have total $N$ one-hop transmissions where all neighbors listen, *i.e.,*

$$
\begin{aligned}
\mathcal{E} &= \min_{r \geq r_{\text{min}}} N(E_{\text{tx}} + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) \\
&= \min_{r \geq r_{\text{min}}} N(e_{\text{tx}} + e_{\text{out}} r^{\alpha} + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) \\
&= \left\{ \begin{array}{ll} \mathcal{O}(N \log N) & \rho \uparrow, \; r_0 = 0 \\ \mathcal{O}(N^2) & \rho \uparrow, \; r_0 > 0 \\ \mathcal{O}(N(\log N)^{\alpha}) & R \uparrow \end{array} \right. .
\end{aligned}
$$

## 4. ENERGY EFFICIENCY FOR DATA-CENTRIC APPLICATIONS

We now analyze the network-level energy consumption. We assume here sensors are waken up by an energy detector, *i.e.,* a transmitting node wakes up all its neighbors. Using the basic elements given in Section 3, it is straightforward to obtain the analysis for the case of perfect waken up scheme.

We first consider data-centric applications where sensors with certain measurements need to transmit their data to the access points. In the flat ad hoc architecture, the gateway node first broadcast the request to all sensors in one transmission[1]. Sensors with the requested data then start to transmit to Assume that a fraction $\beta$ of sensors have the requested data, and they are uniformly distributed in the network. We obtain the total energy consumed in completing this request as

$$
\begin{aligned}
\mathcal{E}^{(d)}_{\text{AdHoc}} &= NE_{\text{rx}} + \beta N \min_{r \geq r_{\text{min}}} (E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}})\frac{\bar{x}}{r} \\
&= \left\{ \begin{array}{ll} \mathcal{O}(\sqrt{N^3 \log N}) & \rho \uparrow, \; r_0 = 0 \\ \mathcal{O}(N^2) & \rho \uparrow, \; r_0 > 0 \\ \mathcal{O}(\sqrt{N^3 (\log N)^{\alpha - 1}}) & R \uparrow \end{array} \right.
\end{aligned} \quad (10)
$$

where for simplicity, we have assumed that both the request and the data from sensors contain only one bit.

In SENMA, the mobile access point scans the sensor field and broadcasts the request. Activated sensors with the requested data then transmit directly to the mobile access point. Assume that mobile access point is $H$ away from the activated sensors, we have

$$
\mathcal{E}^{(d)}_{\text{SENMA}} = NE_{\text{rx}} + \beta N E_{\text{tx}}(H) = \mathcal{O}(N). \quad (11)
$$

Shown in Figure 3 are numerical results on the energy consumption. Here we consider increasing the network size by increasing the density $\rho$. The shape of the curves confirms the scaling laws given in (10,11). Orders of magnitude of improvement in energy efficiency can be achieved by SENMA in large scale sensor networks.

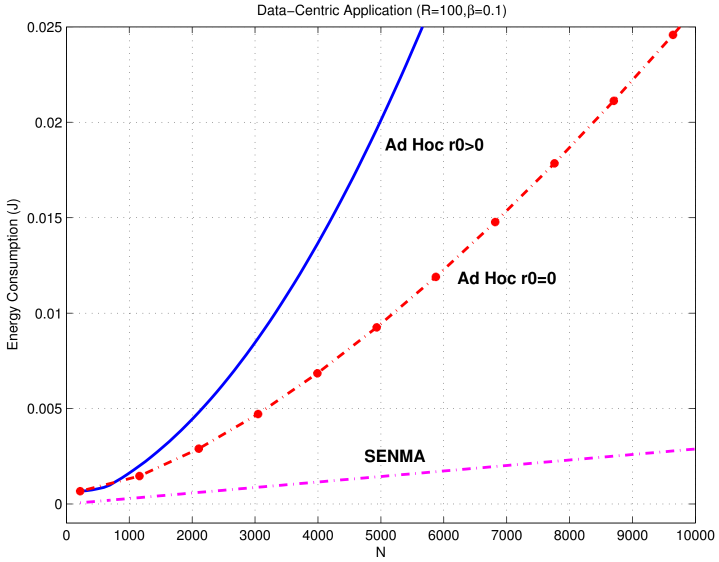

**Fig. 3**: Energy consumption for data-centric applications.

## 5. ENERGY EFFICIENCY FOR LOCATION-CENTRIC APPLICATIONS

In location-centric applications, the access point is interested in a particular geographic location in the sensor field. For the flat ad hoc architecture, the gateway node transmits the request to the area of interest using a predetermined route. One of the sensors located in the area of interest then transmits its measurement to the gateway node. Using the

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[1] If the gateway node can not reach all sensors in one hop, the request needs to be flooded over the network in multiple hops. The analysis given in Section 3.4 can be applied here to derive the network-level energy consumption.

basic elements given in Section 3, we have

$$
\begin{aligned}
\mathcal{E}^{(q)}_{\text{AdHoc}} &= 2 \min_{r \geq r_{\min}} (E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}})\frac{\bar{x}}{r} \\
&= \left\{ \begin{array}{ll} \mathcal{O}(\sqrt{N \log N}) & \rho \uparrow,\ r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow,\ r_0 > 0 \\ \mathcal{O}(\sqrt{N (\log N)^{\alpha-1}}) & R \uparrow \end{array} \right. \quad (12)
\end{aligned}
$$

In SENMA, the mobile access point moves to the area of interests and activates sensors located in that area. Let $d$ denote the radius of the coverage area of the mobile access point. The total energy consumption is given by

$$
\mathcal{E}^{(q)}_{\text{SENMA}} = \min_{d \geq d_0} \frac{d^2}{R^2} N E_{\text{rx}} + E_{\text{tx}}(H), \qquad (13)
$$

where $d_0$ is the hardware limit on the minimum radius of the coverage area.

First, consider the network size $N$ is increased by increasing the node density $\rho$. If $d_0 > 0$, a fixed fraction $d_0^2/R^2$ of the network population will be activated by the mobile access points. The energy consumption thus scales with $N$. If, on the other hand, $d_0 = 0$, we can then shrink the converge area so that the number of activated sensors remains constant. The total energy consumption is thus constant.

When the network size $N$ is increased by increasing the network radius $R$, the hardware limit $d_0$ is irrelevant. The number of activated sensors does not grow with the network size, resulting in constant energy consumption. The scaling behavior of the total energy consumption in SENMA is given by

$$
\mathcal{E}^{(q)}_{\text{SENMA}} = \left\{ \begin{array}{ll} \mathcal{O}(1) & \rho \uparrow,\ d_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow,\ d_0 > 0 \\ \mathcal{O}(1) & R \uparrow \end{array} \right. \qquad (14)
$$

Shown in Figure 4 are numerical results where the network size is increased by increasing $\rho$. These results agree with the scaling laws given by (12,14) and demonstrate the potential gain achieved by SENMA in large sensor networks.

## 6. CONCLUSION

A key objective of connectionless networking is energy efficiency, which makes the connectionless paradigm especially appropriate to sensor networks. We presented in this paper an analytical framework for evaluation energy consumption of specific networking strategies. The analytical expressions obtained in this paper, especially those basic analysis components presented in Section 3 can be applied to other situations and networking strategies [23].

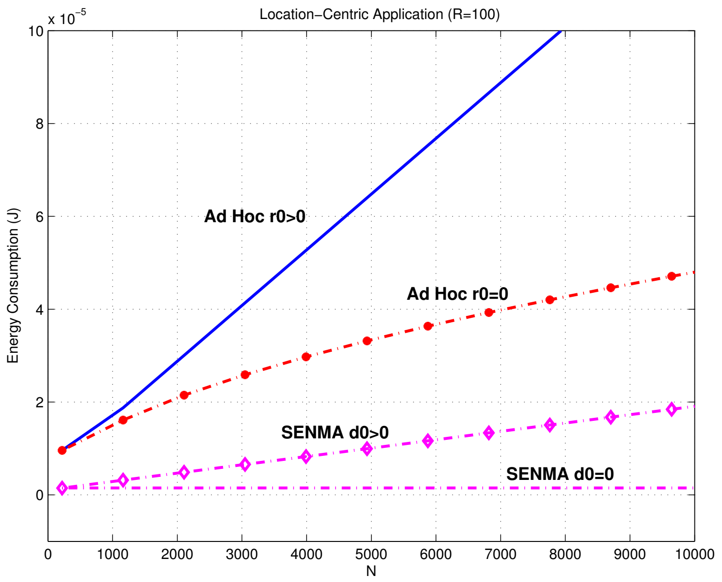

**Fig. 4**: Energy consumption for location-centric applications.

A few cautionary remarks are in order when we examine the comparison between the flat ad hoc sensor networks and SENMA. Specifically, the energy consumed by the mobile AP is not included in the overall calculation for SENMA. The assumption is that the mobile AP is not energy constrained and the energy source is renewable. Because the derivation is based on asymptotic results, the analytical expressions are valid for large scale networks, say, hundreds of nodes.

Sensor networks may operate in drastically different states, from passive monitoring to active responding to certain events. What is needed is an adaptive connectionless networking strategy that allow the network operating seamlessly for various traffic demands and traffic patterns. One such an approach is considered in [24].

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