Modeling and Analysis of Wildfire Detection using Wireless Sensor Network with Poisson Deployment

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Introduction: Forest fire and its impact

- Wild-fire is one of the most dangerous calamity.

- 50% of the total forest cover in India is affected by occasional forest fire.

| Type of fire damage | Percent area of forest (%) | Area of forest in sq. km. |
|---------------------|---------------------------|--------------------------|
| Very high           | 0.84                      | 5426.664                 |
| High                | 0.14                      | 949.6662                 |
| Frequent            | 5.16                      | 35001.9828               |
| Occasional          | 43.06                     | 292090.1898              |
| No fire             | 50.80                     | 317188.5108              |
| Total               | 100                       | 650657.0136              |

Data on Forest fire prone forest area in India [1].

| Year     | Himachal Pradesh | Uttarakhand |
|----------|------------------|-------------|
|          | No. of Forest Fires | Total area affected (In ha.) | Total loss estimated (In ₹) | No. of Forest Fires | Total areas affected (In ha.) | Total loss estimated (In ₹) |
| 2013-14  | 397              | 3237.52     | 52,31,011   | 245          | 384.05                     | 4,39,387                  |
| 2014-15  | 725              | 6726.49     | 1,13,26,522 | 515          | 930.33                     | 23,57,707                 |
| 2015-16  | 672              | 5749.95     | 1,34,77,730 | 412          | 701.61                     | 7,94,356                  |
| 2016-17  | 1545             | 13069.00    | 1,53,58,143 | 2074         | 4433.75                    | 46,50,225                 |

Some event of forest fire associated loss and area affected by the fire [2].

- An early warning alarm system can prevent such huge loss of property.

[1] Satendra and A. D. Kaushik, Forest Fire Disaster Management. National Institute of Disaster Management, Ministry of Home Affairs, Government of India New Delhi, 2014.
[2] R. Sabha, “One hundred forty-ninth report on action taken by the department of science & technology on the recommendations contained in the one hundred fortieth report of the department-related parliamentary standing committee on science and technology, environment & forests on the demands for grants (2005-2006) of the department of science & technology,” Rajya Sabha Secretariat, New Delhi, 2005.
Early Warning System

➢ An early warning system can be developed by using a wireless sensor network.

➢ A wireless sensor network is a group of specialized transducer with a communications infrastructure for monitoring and recording conditions at diverse locations.

Contribution: This paper proposes a technique to compute coverage probability of wireless fire sensor network under different fire propagation model.

Real-time monitoring of forest fire being used by forest survey of India.
System Model

➢ Location of sensors $x_i$ are modeled as homogenous Poisson point process (PPP).

➢ Homogenous PPP implies that sensors nodes are uniformly and randomly located throughout the forest.

➢ Each sensor node have random sensing range.

➢ Ignition of forest fire is considered to be an event which is growing with time.

➢ An event is said to be detected when fire comes under the sensing region of a sensor.

➢ $S_i$: denote the ball of random radius at origin.

➢ Hence the total occupied area by sensors is given by: $\zeta = \bigcup_{i \in N} x_i + S_i.$
Description of Sensor Node

- Sensor have random sensing range:

\[ r = r_{\text{in}} + y. \]

- Here \( y \) is a truncated exponential random variable for with probability density function:

\[
    f(y) = \begin{cases} 
        \frac{e^{-y}}{1-e^{-R'}} & \text{if } 0 < y \leq R' \\
        0 & \text{otherwise.}
    \end{cases}
\]

- Important parameter associated with sensing range

\[
    E[r] = \frac{1 + r_{\text{in}} - (1 + r_{\text{out}})e^{-(r_{\text{in}}-r_{\text{out}})}}{1 - e^{-(r_{\text{in}}-r_{\text{out}})}}
\]

\[
    E[r^2] = r_{\text{in}}^2 + 2E[y](1 + r_{\text{in}}) - \frac{R'^2e^{-R'}}{1 - e^{-R'}}.
\]
Fire Propagation Model

- A fire ignited at point will increase with time in area.
- The fire envelope might take the following shapes.
  A) Elliptical Propagation Model
  B) Circular Propagation Model
  C) Piriform Propagation Model

Elliptical Model

- Increment in the major and minor axis will be according to following eq.
  \[ a(t) = at(1 + \frac{v_x}{V}) \]
  \[ b(t) = at(1 + \frac{v_y}{V}). \]

- Here \( v_x, v_y \) are the wind velocity in \( x \) and \( y \) direction respectively.
Circular Propagation Model

➢ Circular model is special case of elliptical model.

➢ In the absence of wind the elliptical model converges to a circular model.

➢ In the absence of wind the fire will propagation in all direction with same some fix velocity.

\[ r_K(t) = \alpha t. \]
What if wind velocity is high??

➢ Wind act as a catalyst in fire propagation.

➢ In higher wind velocity fire envelop will no longer be elliptical.

➢ The growth of fire envelop in one direction will be higher than the other direction.

➢ In this case the fire envelop will take piriform shape.

➢ The fire envelop is given by:

\[ K(t) = \left\{ x, y : \begin{align*}
    x &= a(t)(1 + \sin \phi) \\
    y &= b(t) \cos \phi (1 + \sin \phi)
\end{align*} \right\}, \quad 0 \leq \phi \leq 2\pi \]

➢ The axial velocity is given by:

\[ a(t) \approx \alpha t (1 + \frac{v}{v}) \]

\[ b(t) \approx \alpha t. \]
Coverage Analysis

➢ An event of fire will be said to be not sensed as: \( \xi \cap \mathcal{K}(t) = \emptyset \).

Fire sensing probability:

➢ A fire event is not sensed at time \( t \) is given by:
\[
G(t) = \mathbb{P}(\xi \cap \mathcal{K}(t) = \emptyset) = \exp(-\lambda \mathbb{E}(A(\hat{S} \oplus \mathcal{K}(t))))
\]

\( \hat{S} \): is the mirror image of \( S \)

➢ Therefore the fire sensing probability would be:
\[
p(t) = 1 - G(t) = 1 - \exp(-\lambda \mathbb{E}[A(\mathcal{K}(t) \oplus \hat{S})]).\]

\( N(\mathcal{K}(t)) \): The mean number sensor that have detected the fire in their sensing range.

\( A(\mathcal{K}(t) \oplus \mathcal{B}(0, r)) \): Denote the area of Minikowski sum and can be evaluated by Stiner Formula.
\[
A(\mathcal{K}(t) \oplus \mathcal{B}(0, r)) = A(\mathcal{K}(t)) + \ell(\mathcal{K}(t))r + \pi r^2.
\]
Contd...

**Fire detection probability:**

➢ Any part of the fire region falls in the sensing region of at least one sensor at critical time.

\[ p_f = \mathbb{P}(\xi \cap \mathcal{K}(t_{cr}) \neq \emptyset). \]

\( \mathcal{K}(t_{cr}) \): is the area of fire envelop at critical time.

➢ The critical time is the time window under which the fire is controllable.

➢ Hence, the fire detection probability is if fire is detected before the critical time:

\[ p_f = 1 - \exp(-\lambda \mathbb{E} [\mathcal{A}(\mathcal{K}(t_{cr}) \oplus \hat{S})]). \]
➢ **Critical sensor density:** Critical sensor density is the density of sensor which can detect the fire with a fix probability before it turns critical.

\[ \lambda_{cr} : \tau = p_f = 1 - \exp(-\lambda_{cr} \mathbb{E}[\mathcal{K}(t_{cr}) \oplus \hat{S}] ) . \]

\[ \lambda_{cr}(\tau) = \frac{1}{\mathbb{E}[\mathcal{A}(\mathcal{K}(t_{cr}) \oplus \hat{S} ]} \log \left( \frac{1}{1 - \tau} \right) . \]

➢ **In the absences of wind (circular propagation model):**

\[ p_f(t) = 1 - \exp \left( -\lambda \pi \left[ (\alpha t_{cr})^2 + 2\alpha t_{cr} \mathbb{E}[r] + \mathbb{E}[r^2] \right] \right) . \]
The critical time will be given by:

\[ t_{cr} \leq \frac{1}{\alpha} \sqrt{\frac{A_{cr}}{\pi}}. \]

\[ \lambda_{cr}(\tau) = \frac{1}{\pi(\alpha t_{cr})^2 + 2\pi \alpha t_{cr} \mathbb{E}[r] + \pi \mathbb{E}[r^2]} \ln \left( \frac{1}{1 - \tau} \right) \]

Similarly fire detection probability for elliptical and piriform model can be evaluated.

Critical sensor density in presence of wind (Elliptical Model):

\[ \lambda_{cr} = \frac{1}{[\pi a(t_{cr}) b(t_{cr}) + \ell(C(t_{cr})) \mathbb{E}[r] + \pi \mathbb{E}[r^2]]} \log \left( \frac{1}{1 - \tau} \right) \]

Critical sensor density in presence of wind (Piriform Model):

\[ \lambda_{cr} = \frac{1}{A_{cr} + \ell \left( C \left( \frac{1}{\alpha} \sqrt{\frac{A_{cr}}{\pi(1 + \frac{\rho}{\sqrt{r}})}} \right) \right) \mathbb{E}[r] + \pi \mathbb{E}[r^2]} \log \left( \frac{1}{1 - \tau} \right). \]
Results and Discussion

➢ The numerical parameters taken are as follows:

| Parameter                                           | Value                  |
|-----------------------------------------------------|------------------------|
| Inner sensing range ($r_{in}$)                      | 2 meter                |
| Outer sensing range ($r_{out}$)                     | 4 meter                |
| $\mathbb{E}[r]$ and $\mathbb{E}[r^2]$               | 2.68 meter, 5.49 meter |
| Fire flame velocity ($\alpha$)                      | .33 meter/sec.         |
| Critical area ($A_{cr}$)                            | 20 m$^2$               |
| Wind velocity ($v_x$) in elliptical/piriform model | 3 m/s                  |
| Scaling factor (V)                                  | 10 m/s                 |
Fire detection probability (circular fire propagation)

➢ Fire detection probability gradually increases with sensor density.

➢ The sensor density around 0.1 sensor/m$^2$ provide fire detection probability more than 80%.
Fire detection probability (elliptical and piriform model)

- In elliptical propagation model we need lesser sensor density.

- A sensor density of 0.04 sensors/m² can provide detection probability more than 80% within sufficient time (within 4 second) window.

- In piriform propagation model 0.03 sensors/m² of sensor density which is less than elliptical propagation model can provide the same performance.
Does wind help??

- In the circular propagation model critical time $t_{cr} = 7.6$ seconds.
- The critical time in the presence of wind decreases to 6.7 seconds.
- Reduction in the critical time is due to faster spread of fire.
- Critical time for elliptical and piriform model is same.
- However piriform model provide better fire sensing probability due to larger area to perimeter ratio.
Impact of wind velocity on critical sensor density

- The critical sensor density reduces in piriform type propagation as compared to elliptical type propagation of fire.

- In high winds, critical time reduces which is one of critical concern.

- The fire detection probability threshold also increases.

Critical sensor density with respect to wind velocity for different values of fire detection probability threshold.
Conclusion

➢ In this paper, we have considered a WSN with fire sensors for early detection of the forest fire.

➢ We present an analytical framework based on the Boolean-Poisson model, with the elliptical, circular and piriform fire flame propagation.

➢ We compute the critical sensor density which needs to be deployed in the forest to ensure a certain minimum fire detection probability.

➢ It has identified that in the presence of wind, critical time to detect fire decreases but the fire sensing probability also increases.

➢ The work provides an estimate the sensor density in forest.

Future Work:
➢ A more specific model can be generated depending on the forest conditions.
➢ Sensors can also be used for sensing different environmental condition in the forest.
➢ A more generic fire propagation model can be used for more accurate analysis.
Thank You