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.

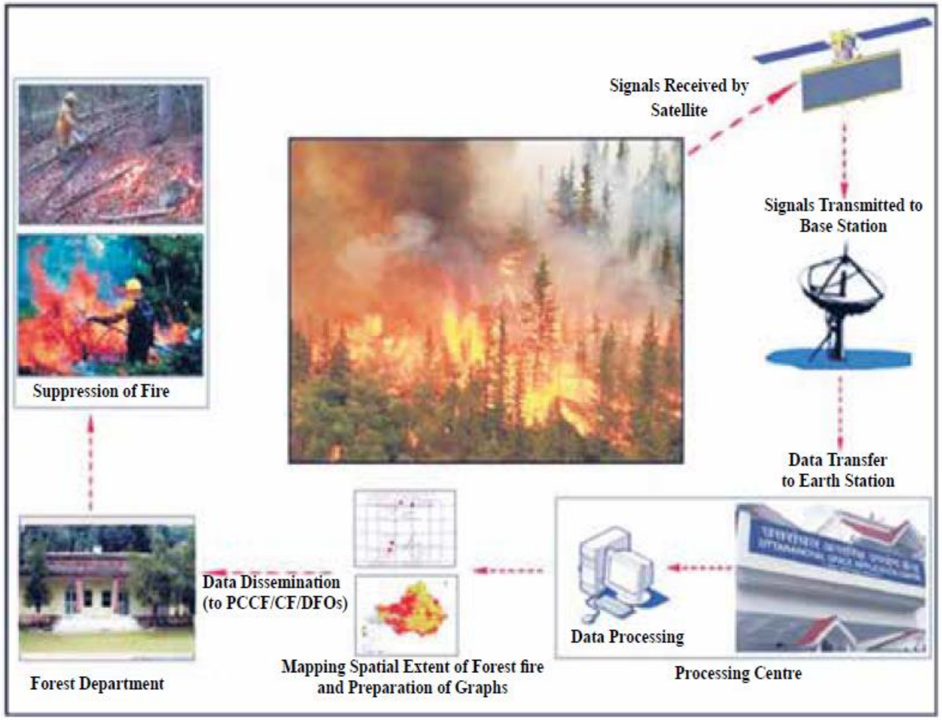
[1] Satendra and A. D. Kaushik, Forest Fire Disaster Management. National Institute of Disaster Management, Ministry of Home Affairs, Government of India New Delhi, 2014.
[2] R. Sabha, "One hundred forty-ninth report on action taken by the department of science & technology on the recommendations contained 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.

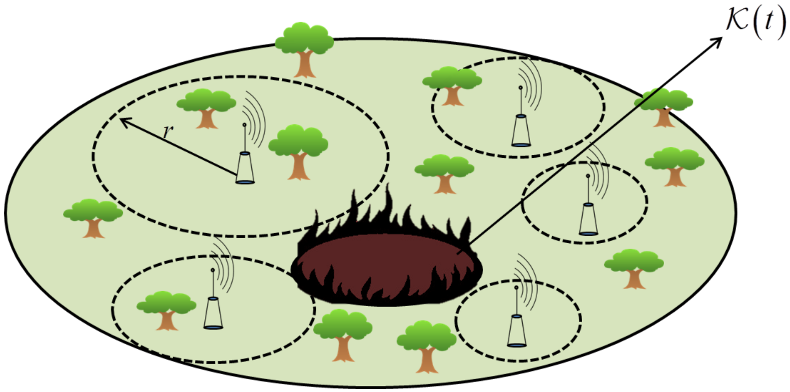
Contribution: This paper proposes a technique to compute coverage probability of wireless fire sensor network under different fire propagation model.



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: $\xi = \bigcup_{i \in N} x_i + S_i.$



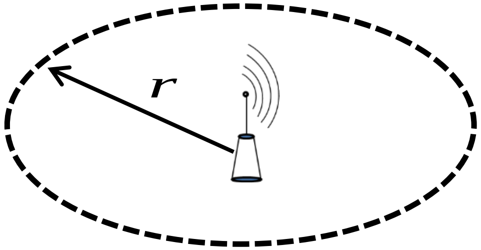
Network of wireless fire sensors deployed over the forest.

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:



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

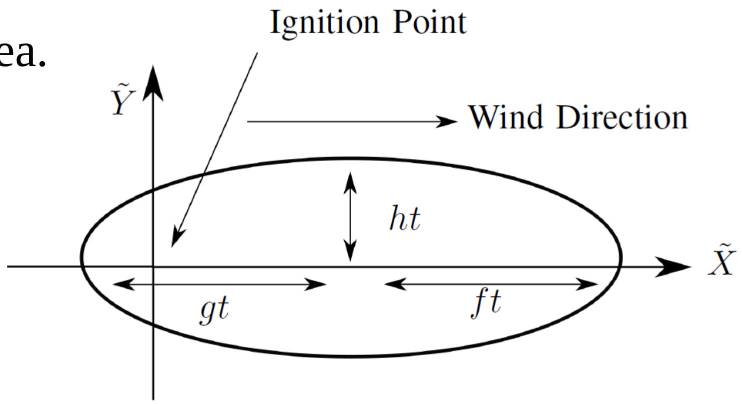
- Important parameter associated with sensing range

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

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

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.

$$a(t) = \alpha t(1+\frac{v_x}{V})$$

$$b(t) = \alpha t(1+\frac{v_y}{V}).$$

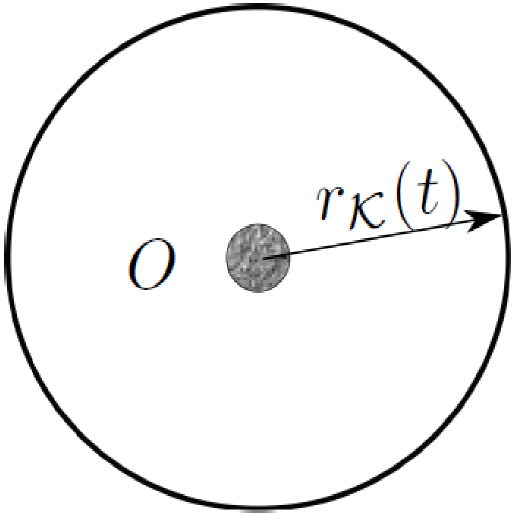
- Here v_x, v_y are the wind velocity in x and y direction respectively.

Circular Propagation Model

- Circular model is special case of elliptical model.

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

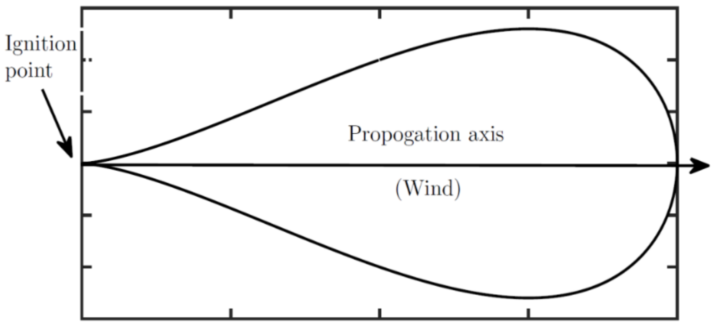
- In the absence of wind the fire will propagation in all direction with same some fix velocity.



$$r_K(t) = \alpha t.$$

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:

$$\mathcal{K}(t) = \left\{ x, y : \begin{array}{l} x = a(t)(1+\sin\phi) \\ y = b(t)\cos\phi(1+\sin\phi) \end{array}, 0 \le \phi \le 2\pi \right\}.$$

- The axial velocity is given by: $a(t) \approx \alpha t(1 + \frac{v_x}{V})$, $b(t) \approx \alpha t.$

Coverage Analysis

Recall coverage

$$\xi = \bigcup_{i \in N} x_i + \mathsf{S}_i.$$

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

Fire sensing probability:

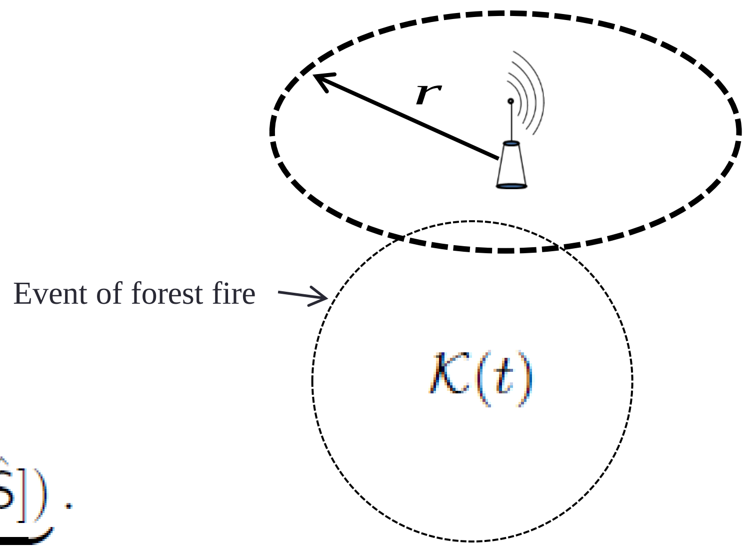
- A fire event is not sensed at time *t* is given by:

$$\begin{aligned} \mathcal{G}(t) &= \mathbb{P}(\xi \cap \mathcal{K}(t) = \phi) \\ &= \exp(-\lambda \mathbb{E}(\mathcal{A}(\hat{\mathsf{S}} \oplus \mathcal{K}(t))) \end{aligned}$$

$\hat{\mathsf{S}}$: is the mirror image of S

- Therefore the fire sensing probability would be:

$$\begin{aligned} p(t) &= 1 - \mathcal{G}(t). \\ &= 1 - \exp(-\underbrace{\lambda \mathbb{E}[\mathcal{A}(\mathcal{K}(t) \oplus \hat{\mathsf{S}}])}_{N(\mathcal{K}(t))}. \end{aligned}$$



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

$\mathcal{A}(\mathcal{K}(t) \oplus \mathcal{B}(0,r))$: Denote the area of Minikowski sum and can be evaluated by Stiner Formula.

$$\mathcal{A}(\mathcal{K}(t) \oplus \mathcal{B}(0,r)) = \mathcal{A}(\mathcal{K}(t)) + \ell(\mathcal{K}(t))r + \pi r^2.$$

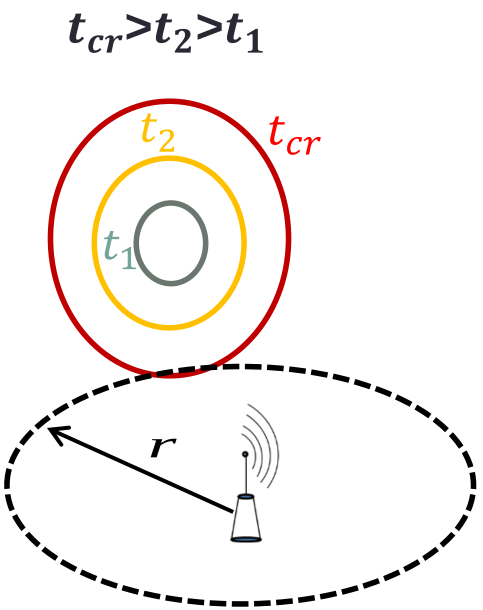
Contd…

Fire detection probability:

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

$$p_{\mathrm{f}} = \mathbb{P}(\xi \cap \mathcal{K}(t_{\mathrm{cr}}) \neq \phi).$$

$\mathcal{K}(t_{\mathrm{cr}})$: 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:

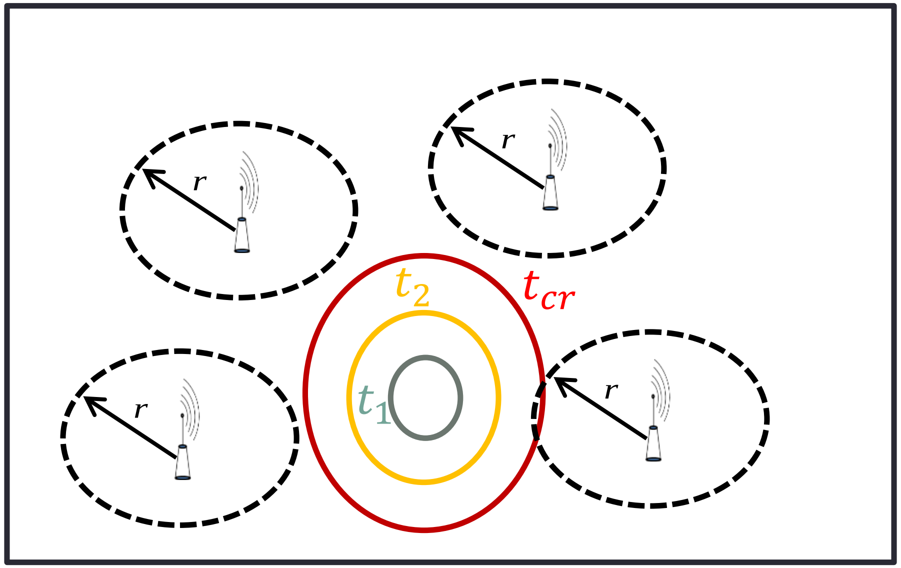
$$p_{\mathrm{f}} = 1 - \exp(-\lambda \mathbb{E}[\mathcal{A}(\mathcal{K}(t_{\mathrm{cr}}) \oplus \hat{\mathsf{S}}])).$$

Contd..

- **Critical sensor density:** Critical sensor density is the density of sensor which can detect the fire with a fix probability before it turns critical.

$$\lambda_{\text{cr}} : \tau = p_{\text{f}} = 1 - \exp(-\lambda_{\text{cr}}\mathbb{E}[\mathcal{A}(\mathcal{K}(t_{\text{cr}}) \oplus \hat{\mathsf{S}}]).$$

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



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

$$p_{\text{f}}(t) = 1 - \exp\left(-\lambda\pi\left[(\alpha t_{\text{cr}})^2 + 2\alpha t_{\text{cr}}\mathbb{E}[r] + \mathbb{E}[r^2]\right]\right).$$

Contd…

- The critical time will be given by:

$$t_{\mathrm{cr}} \leq \frac{1}{\alpha}\sqrt{\frac{A_{\mathrm{cr}}}{\pi}}.$$

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

- Similarly fire detection probability for elliptical and piriform model can be evaluated.
- **Critical sensor density in presence of wind (Elliptical Model):**

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

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

$$\lambda_{\mathrm{cr}} = \frac{1}{A_{\mathrm{cr}} + \ell\left(\mathcal{K}\left(\frac{1}{\alpha}\sqrt{\frac{A_{\mathrm{cr}}}{\pi(1+\frac{v_x}{V})}}\right)\right)\mathbb{E}[r] + \pi\mathbb{E}[r^2]} \log\left(\frac{1}{1-\tau}\right).$$

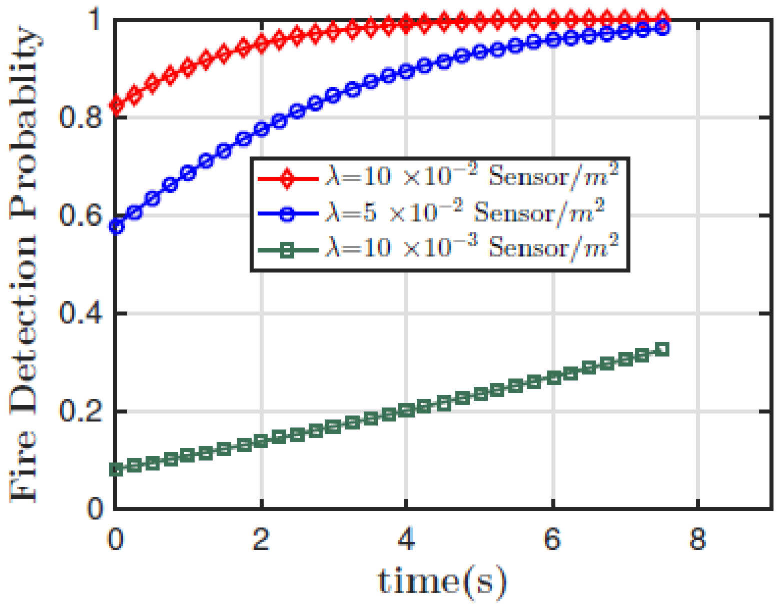
Results and Discussion

- 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 (α)	.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)

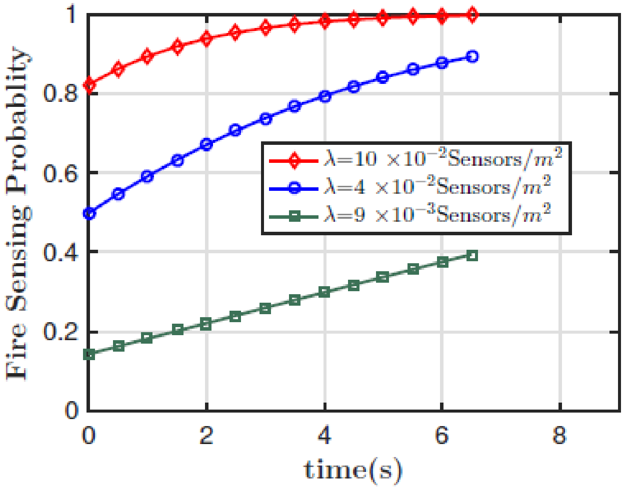
- Fire detection probability gradually increases with sensor density.
- The sensor density around 0.1 *sensor/m*^{2} provide fire detection probability more than 80%.



Fire detection probability (elliptical and piriform model)

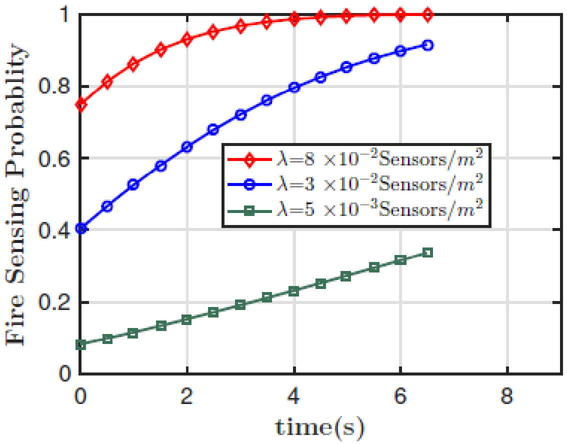
- In elliptical propagation model we need lesser sensor density.

- A sensor density of 0.04 sensors/m^2 can provide detection probability more than 80% within sufficient time (within 4 second) window.



Elliptical model.

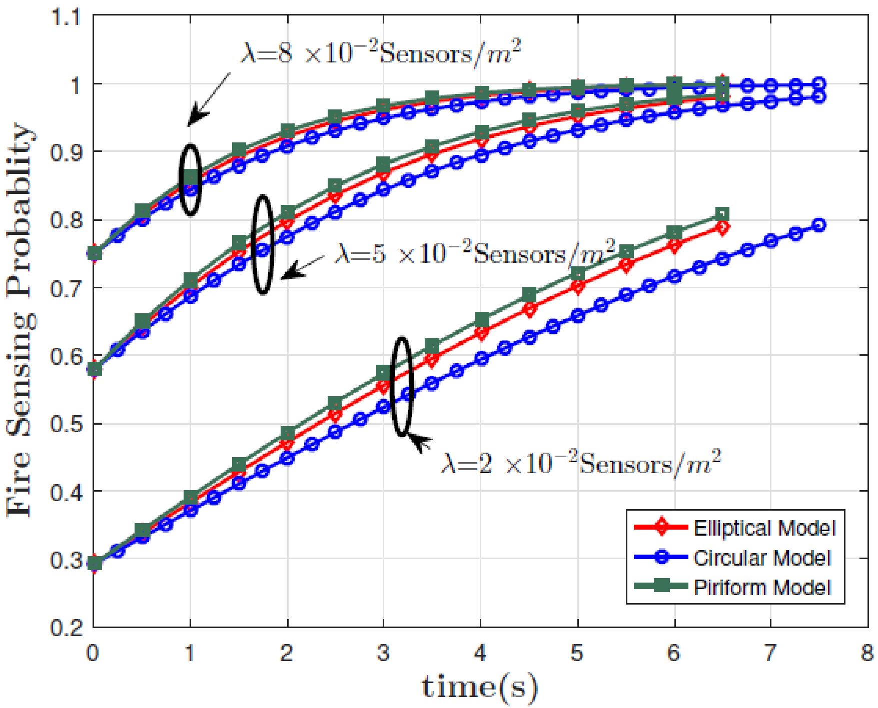
- In piriform propagation model 0.03 sensors/m^2 of sensor density which is less than elliptical propagation model can provide the same performance.



Piriform model.

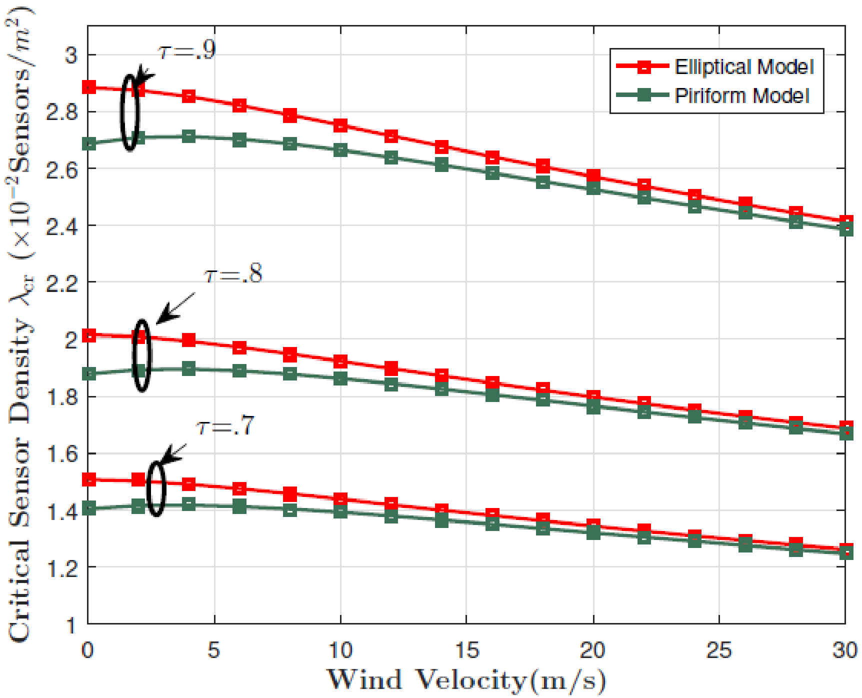
Does wind help??

- 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