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# FALSE ALARMS IN FAULT-TOLERANT DOMINATING SETS IN GRAPHS

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**Abstract.** We develop the problem of fault-tolerant dominating sets (liar's dominating sets) in graphs. Namely, we consider a new kind of fault – a false alarm. Characterization of such fault-tolerant dominating sets in three different cases (dependent on the classification of the types of the faults) are presented.

**Keywords:** liar's dominating set, fault-tolerant dominating set, false alarm, Hamming distance.

**Mathematics Subject Classification:** 05C69, 94B99.

## 1. INTRODUCTION

Let $G = (V, E)$ be a simple graph. A set $D \subset V$ is said to be a *dominating set* in $G$ if $N[v] \cap D \neq \emptyset$ for every $v \in V$, where $N[v]$ denotes the closed neighbourhood of $v$ i.e.

$$N[v] := \{v\} \cup \{u \in V | uv \in E\}.$$

Fault-tolerant dominating sets (named by the author as a liar's dominating set) were introduced by P.J. Slater in [7] as follows. Consider a structure that could be represented by a graph (a computer, electrical, or sensor network, a floor-plan of a museum, a road network, etc.), where each vertex indicates some network location. In each network location there might appear some undesired event, and its location has to be determined. In some locations there are detectors (monitors, sensors) which are responsible for reporting on the presence and location of this undesired events in its closed neighbourhood.

We assume that in any point of time at most one undesired event can occur.

Let $D \subset V$ be a set of detectors. Each detector $x \in D$ reports the location of an undesired event in its closed neighbourhood (if such is detected) or reports no location (if no undesired event is detected). All reports are collected in, say, the centre of information. The final conclusion on the existence and, eventually, location of an undesired event is based on the reports of all detectors.

We consider the case that under some circumstances detectors may fail in their reporting. In the basic, introduced in [7], model we assume that at most one detector $x \in D$ makes a fault of type $A$ or $B$, defined as follows.

**Definition 1.1.** We distinguish the following types of detector's $x \in D$ faults:

— Fault of type $A$ (false negative): failing to report the existence of an undesired event in $N[x]$;
— Fault of type $B$ (false identification): reporting a wrong location (i.e. reporting $u$, while an undesired event is at $v \neq u$, where $u, v \in N[x]$).

It is important to underline the difference between this model and the problem of fault-tolerant locating-dominating sets considered i.e. by Slater [6], where detectors are not indicating the precise location of an undesired event but just reporting that they occur in their neighbourhood. The latter one is related to locating-dominating sets [4, 5] and metric bases in graphs, considered by Harary and Melter [2].

The following definition and theorem are adapted from [3] and [7] with use of the above notation.

**Definition 1.2.** A set $D \subset V$ is called a $(A \vee B)$-*fault-tolerant dominating set* if the presence and location of an undesired event at any given vertex $v \in V$ can be correctly inferred from the set of reports sent from all vertices in $D$, given that at most one vertex in $D$ sends a faulty report of type $A$ or type $B$.

**Theorem 1.3** ([3])**.** *Set $D$ is a $(A \vee B)$-fault-tolerant dominating set if and only if the following conditions* (1.1) *and* (1.2) *are simultaneously satisfied:*

$$\text{for every } v \in V \ |N[v] \cap D| \geq 2, \tag{1.1}$$

$$\text{for every distinct } u, v \in V \ |(N[u] \cup N[v]) \cap D| \geq 3. \tag{1.2}$$

Let us introduce necessary terminology of reporting vectors, to be used in further sections. Let $D = \{x_1, \ldots, x_m\} \subset V$ be a set of detectors. Then we define a *reporting vector* $\mathbf{a} = \mathbf{a}(D) = (a_1, \ldots, a_m)$, where $a_i$ is indicating the $x_i$'s reporting; $a_i \in V \cup \emptyset$, $i = 1, \ldots, m$. The notation $a_i = \emptyset$ is used if $x_i$ is reporting no location of an undesired event (see Figure 1).

**Definition 1.4.** An $m$-dimensional vector $\mathbf{a}^u$ is called a *$u$-faultless reporting vector* if each of $m$ detectors reports correctly, assuming that there is an undesired event at the vertex $u$.

Now let us recall the Hamming distance.

**Definition 1.5** ([1])**.** Consider two vectors $\mathbf{a}, \mathbf{b} \in W^m$ where $W$ is a given set. The function $d : W^m \times W^m \to \mathbb{N}$ such that

$$d(\mathbf{a}, \mathbf{b}) := |\{i : a_i \neq b_i\}|$$

is called the *Hamming distance*. In our considerations $W = V \cup \{\emptyset\}$.

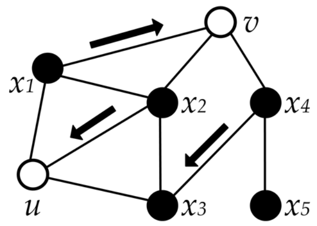


**Fig. 1.** The presented reporting vector is $\mathbf{a} = (v, u, \emptyset, x_3, \emptyset)$, while $\mathbf{a}^u = (u, u, u, \emptyset, \emptyset)$ and $\mathbf{a}^v = (v, v, \emptyset, v, \emptyset)$

## 2. FALSE ALARMS

Let us consider a third type of fault that may occur in the report sent by a vertex in a fault-tolerant dominating set, namely a false alarm, or false positive.

**Definition 2.1.** *False alarm* is a fault that occurs when a vertex $x \in D$ reports the existence of an undesired event at a vertex $v \in N[x]$ when, in fact, this condition does not exist at any vertex $v \in N[x]$. A false alarm is called a fault of type $C$.

**Definition 2.2.** Set of detectors $D \subset V$ is called a $k(A \vee B \vee C)$*-fault-tolerant dominating set* if the presence and location of an undesired event at any given vertex $v \in V$ can be correctly inferred from the set of reports sent from all vertices in $D$, given that at most $k$ vertices in $D$ sends a faulty report of type $A$, type $B$ or type $C$.

**Theorem 2.3.** *Set $D$ is a $k(A \vee B \vee C)$-fault-tolerant dominating set if and only if for every $u \in V$*

$$|N[u] \cap D| \geq 2k + 1. \tag{2.1}$$

*Proof.* Assume that (2.1) is satisfied. Observe that an undesired event is at $u$ if and only if there are at least $k + 1$ detectors reporting $u$. This criterion guarantees that any location of an undesired event can be correctly identified, hence $D$ is an $k(A \vee B \vee C)$-fault-tolerant dominating set.

Conversely, if (2.1) is not satisfied, then there exists $u \in V$ such that $|N[u] \cap D| = t \leq 2k$. Consequently, there exist $t_1, t_2 \in \{0, 1, \ldots, k\}$ such that $t = t_1 + t_2$. Then if $t_1$ detectors of $N[u]$ report $u$ and $t_2$ these detectors report $\emptyset$, we cannot distinguish if there is an undesired event at $u$ (with $t_2$ faults of type A) or there is no such event (with $t_1$ faults of type $C$). □

## 3. ON SENSITIVITY AND SPECIFICITY OF DETECTORS

The faults of the detectors may be caused by too low sensitivity or too low specificity. It seems natural to assume that a vertex in $D$ has at most one of these two drawbacks. We can interpret that having too low sensitivity means the possibility of a wrong reaction if there is an undesired event in the detector's closed neighbourhood. On the other hand having too low specificity can cause a wrong reaction if there is no undesired event.

Assuming that the producer of detectors guarantees that at most $k$ detectors have too low sensitivity and at most $l$ have too low specificity, we formally define:

**Definition 3.1.** Set of detectors $D \subset V$ is called a $(k(A \vee B) + lC)$-*fault-tolerant dominating set* if the presence and location of an undesired event at any given vertex $v \in V$ can be correctly inferred from the set of reports sent from all vertices in $D$, given that at most $k$ vertices in $D$ send a faulty report of type $A$ or type $B$ and at most $l$ vertices in $D$ sends a faulty report of type $C$.

**Theorem 3.2.** *Set $D$ is a $(k(A \vee B) + lC)$-fault-tolerant dominating set if and only if conditions* (3.1) *and* (3.2) *are simultaneously satisfied:*

$$\text{for every } v \in V \ |N[v] \cap D| \geq k + l + 1, \tag{3.1}$$

$$\text{for every distinct } u, v \in V, \text{ at least one of } (3.2a) - (3.2d) \text{ is satisfied:} \tag{3.2}$$

(3.2$a$) $|(N[u] \cup N[v]) \cap D| \geq 2k + 2l + 1,$
(3.2$b$) $|N[u] \cap N[v] \cap D| \geq 2k + 1,$
(3.2$c$) $|N[u] \cap D| \geq 2k + l + 1,$
(3.2$d$) $|N[v] \cap D| \geq 2k + l + 1.$

*Proof.* Let $D$ be a set satisfying conditions (3.1) and (3.2). Then the procedure of identifying the undesired events location is the following:

(i) If there is no vertex reported at least $l + 1$ times, we conclude that there is no undesired event in $G$.
(ii) If there is only one vertex $v$ reported at least $l + 1$ times then $v$ is the undesired event's location.
(iii) If there are exactly two vertices $u, v$ reported at least $l + 1$ times then one of them is the true location. The criterion of identification is following:
   - Vertices $u, v$ satisfying (3.2$a$).
     If $d(\mathbf{a}^u, \mathbf{a}) \leq k + l$ then $u$ is the undesired event's location, otherwise it is $v$. To show that, it is enough to notice that
     $$d(\mathbf{a}^u, \mathbf{a}^v) \geq 2k + 2l + 1,$$
     and (because at most $k + l$ detectors can report incorrectly)
     $$d(\mathbf{a}^u, \mathbf{a}) \leq k + l \Leftrightarrow d(\mathbf{a}^v, \mathbf{a}) \geq k + l + 1.$$
   - Vertices $u, v$ satisfying (3.2$b$).
     In this case we consider the reporting vector restricted to the set
     $$Y := N[u] \cap N[v] \cap D. \tag{3.3}$$
     If $d(\mathbf{a}^u|_Y, \mathbf{a}|_Y) \leq k$, then an undesired event is at $u$, otherwise it is at $v$. It is a consequence of the fact that only $k$ detectors of $Y$ can make a fault. Since
     $$d(\mathbf{a}^u|_Y, \mathbf{a}^v|_Y) \geq 2k + 1,$$

we get

$$d\left(\mathbf{a}^u|_Y, \mathbf{a}|_Y\right) \le k \Leftrightarrow d\left(\mathbf{a}^v|_Y, \mathbf{a}|_Y\right) \ge k+1.$$

- Vertices $u, v$ satisfying (3.2$c$).
  Here we consider the reporting vector restricted to the set

  $$T = (N[u] \cup N[v]) \cap D.$$

  Moreover, let us define

  $$X_{vu} := (N[v] \cap D) \setminus N[u],\ \ s_{vu} := |X_{vu}|. \tag{3.4}$$

  If $s_{vu} \ge l$ then, in fact, the condition (3.2$a$) is satisfied, therefore we only consider the case $s_{vu} < l$. The criterion is as follows: if $d\left(\mathbf{a}^u|_T, \mathbf{a}|_T\right) \le k + s_{vu}$ then an undesired event is at $u$, otherwise it is at $v$.
  Let us show correctness of this criterion. Observe that

  $$d\left(\mathbf{a}^u|_T, \mathbf{a}^v|_T\right) \ge 2k + l + 1 + s_{vu}.$$

  If there is an undesired event at $u$, then at most $k$ detectors from $N[u] \cap D$ can make a fault of type $A$ or $B$, and at most $s_{vu}$ detectors from $X_{vu}$ can cause a fault of type $C$. Then,

  $$d\left(\mathbf{a}^u|_T, \mathbf{a}|_T\right) \le k + s_{vu}.$$

  If $v$ is an undesired event's location then

  $$d\left(\mathbf{a}^v|_T, \mathbf{a}|_T\right) \le k + l$$

  and, consequently

  $$d\left(\mathbf{a}^u|_T, \mathbf{a}|_T\right) \ge (2k + l + 1 + s_{vu}) - (k + l) = k + s_{vu} + 1.$$

- Vertices $u, v$ satisfying (3.2$d$).
  This case is obviously symmetric to the case (3.2$c$), hence the criterion of identifying the location is analogous. Namely, if $d\left(\mathbf{a}^v|_T, \mathbf{a}|_T\right) \le k + s_{uv}$ then the undesired event is at $v$, otherwise it is at $u$.

(iv) If at least three vertices are reported more than $l + 1$ times, then one of them is the undesired event's location. In this case the criterion of identifying the true location is as follows:
The location is the vertex $w$ satisfying

$$d\left(\mathbf{a}^w, \mathbf{a}\right) \le k + l.$$

We only have to show that there is exactly one vertex $w$ with this property. Clearly, there is one vertex $w$ such that $d(\mathbf{a}^w, \mathbf{a}) \le k + l$ because not more than $k + l$ detectors can report incorrectly. We have to show that there is no other vertex $v$ such that $d(\mathbf{a}^v, \mathbf{a}) \le k + l$. Let $w$ be the true location of an undesired event and $v \ne w$ be some other vertex reported at least $l + 1$ times. We show that $d(\mathbf{a}^v, \mathbf{a}) \ge k + l + 1$.

- If $v, w$ are satisfying condition (3.2$a$) then, due to previous arguments, $d(\mathbf{a}^v, \mathbf{a}) \geq k + l + 1$.
- If $v, w$ satisfy (3.2$b$), then at least $k+1$ detectors report $w$ (only $k$ may report incorrectly) and at least $l+1$ other detectors report some vertex different than $v$ and $w$. Hence $d(\mathbf{a}^v, \mathbf{a}) \geq (k+1) + (l+1) > k + l + 1$.
- If $v, w$ satisfy (3.2$c$), i.e. $|N[v] \cap D| \geq 2k + l + 1$, then at least $(2k + l + 1) - (k + l) = k + 1$ detectors of $N[v]$ report the same as in $\mathbf{a}^w$ (i.e. $\emptyset$ or $w$). That means that these $k + 1$ or more detectors report differently than in $\mathbf{a}^v$. Moreover, there are at least $l + 1$ detectors reporting some vertex different than $w$ and $v$, therefore $d(\mathbf{a}^v, \mathbf{a}) \geq (k + 1) + (l + 1) > k + l + 1$.
- In the last case of $v, w$ satisfying (3.2$d$), i.e. $|N[w] \cap D| \geq 2k + l + 1$, we easily observe that at least $(2k + l + 1) - k = k + l + 1$ detectors report $w$, hence $d(\mathbf{a}^v, \mathbf{a}) \geq k + l + 1$.

This completes the proof that set $D$ satisfying conditions (3.1) and (3.2) is a $(k(A \vee B) + lC)$-fault-tolerant dominating set.

Now we show that if at least one of conditions (3.1), (3.2) is not fulfilled then $D$ is not a $(k(A \vee B) + lC)$-fault-tolerant dominating set. If (3.1) is not satisfied then for some vertex $u$ then there exists $k', l'$ such that

$$|N[u] \cap D| = k' + l', \text{ where } k' \in \{0, 1, \ldots, k\}, l' \in \{0, 1, \ldots, l\}.$$

Then clearly $D$ is not a $(k(A \vee B) + lC)$-dominating set, because if $l'$ detectors of $N[u]$ report $u$ and all other detectors report $\emptyset$, we cannot state if there is an undesired event at $u$ or not.

Consider now the case when condition (3.1) is satisfied, but condition (3.2) is not (for some $u, v \in V$). Then all the following conditions (which are negations of statements (3.2$a$)– (3.2$d$)) are satisfied,

$$s_{uv} + s_{vu} + |Y| \leq 2k + 2l, \tag{3.5}$$
$$|Y| \leq 2k, \tag{3.6}$$
$$k + l + 1 \leq s_{uv} + |Y| \leq 2k + l, \tag{3.7}$$
$$k + l + 1 \leq s_{vu} + |Y| \leq 2k + l, \tag{3.8}$$

with $Y$ and $s_{uv}$ as defined in (3.3) and (3.4). First, observe that, due to (3.5),(3.7) and (3.8), $s_{uv}$ and $s_{vu}$ are not greater than $l + k$. Moreover, due to (3.5)-(3.8), there exists non-negative integers $t_u, t_v$ such that $|Y| = t_u + t_v$, and

$$t_v + \max\{0, s_{uv} - l\} \leq k \text{ and } t_u + \max\{0, s_{vu} - l\} \leq k.$$

Consider the following reporting:

— $\min\{l, s_{uv}\}$ detectors of $X_{uv}$ and $t_u$ detectors of $Y$ report $u$,
— $\min\{l, s_{vu}\}$ detectors of $X_{vu}$ and another $t_v$ detectors of $Y$ report $v$,
— all the rest, i.e. $\max\{0, s_{uv} - l\}$ detectors of $X_{uv}$, $\max\{0, s_{vu} - l\}$ detectors of $X_{vu}$ and all the other detectors report $\emptyset$,

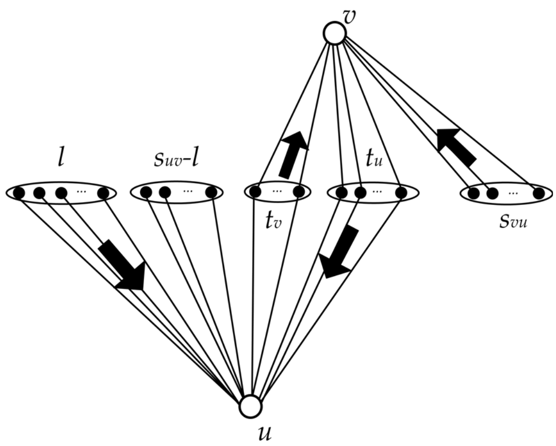


**Fig. 2.** The case when $s_{uv} > l$ and $s_{vu} \leq l$. Both $u$ and $v$ are possible location of an undesired event

In this case both $u$ and $v$ are a possible undesired event's location (Figure 2), namely:

— an event is at $u$, while $\max\{0, s_{uv} - l\}$ detectors of $X_{uv}$ make a fault of type $A$, $t_v$ detectors of $Y$ make a fault of type $B$ and $\min\{l, s_{vu}\}$ detectors of $X_{vu}$ make a fault of type $C$, or
— an event is at $v$, while $\max\{0, s_{vu} - l\}$ detectors of $X_{vu}$ make a fault of type $A$, $t_u$ detectors of $Y$ make a fault of type $B$ and $\min\{l, s_{uv}\}$ detectors of $X_{uv}$ make a fault of type $C$.

This shows that if conditions (3.1) and (3.2) are not simultaneously satisfied then $D$ is not $(k(A \vee B) + lC)$-fault-tolerant dominating set. □

Now let us present some modifications to the interpretation of detectors faults. Namely, one can assume that having too low sensitivity means the possibility of reporting no undesired event, if there is one in a closed neighbourhood (fault of type $A$). On the other hand having too low precision (or specificity) means the possibility of reporting the wrong location (faults of type $B$ or $C$).

**Definition 3.3.** Set of detectors $D \subset V$ is called a $(kA + l(B \vee C))$*-fault-tolerant dominating set* if the presence and location of an undesired event at any given vertex $v \in V$ can be correctly inferred from the set of reports sent from all vertices in $D$, given that at most $k$ vertices in $D$ sends a faulty report of type $A$ and at most $l$ vertices in $D$ sends a faulty report of type $B$ or type $C$.

**Theorem 3.4.** *Set $D$ is a $(kA + l(B \vee C))$-fault-tolerant dominating set if and only if conditions* (3.9) *and* (3.10) *are simultaneously satisfied:*

$$\text{for every } v \in V \ |N[v] \cap D| \geq k + l + 1, \tag{3.9}$$

$$\text{for every distinct } u, v \in V \text{ at least one of } (3.10a) – (3.10c) \text{ is satisfied:} \tag{3.10}$$

(3.10$a$) $|(N[u] \cup N[v]) \cap D| \geq 2k + 2l + 1,$
(3.10$b$) $|N[u] \cap D| \geq k + 2l + 1,$
(3.10$c$) $|N[v] \cap D| \geq k + 2l + 1.$

*Proof.* Let $D$ be a set of vertices for which conditions (3.9) and (3.10) are satisfied. Then the procedure of identifying an undesired event's location is as follows:

(i) If not more than $l$ detectors report the existence of an undesired event, then there is no such event in $G$. Otherwise there is an event somewhere in $G$, which is a simple consequence of the assumption that not more than $l$ faults of type $C$ can occur.
Now consider only the case of the existence of an undesired event in $G$.
(ii) If there is some vertex $v$ reported at least $l + 1$ times then an undesired event is clearly at $v$. It is easy to observe that there is no possibility that more than one vertex is reported more than $l$ times.
(iii) If there is no vertex reported more than $l$ times then an undesired event is in only one vertex $u$ such that $d(\mathbf{a}, \mathbf{a}^u) \leq k + l$.
We have to show that there exists exactly one vertex $u$ with this property. To the contrary assume that there exists $w \neq u$ such that $d(\mathbf{a}, \mathbf{a}^w) \leq k + l$.

— If $u, w$ are satisfying (3.10$a$) then $d(\mathbf{a}^u, \mathbf{a}^w) \leq 2k + 2l + 1$ what leads us to a contradiction to our assumptions that $d(\mathbf{a}, \mathbf{a}^u) \leq k + l$ and $d(\mathbf{a}, \mathbf{a}^w) \leq k + l$.
— If $u, w$ are satisfying (3.10$b$), i.e. $|N[u] \cap D| \geq k + 2l + 1$, then $d(\mathbf{a}, \mathbf{a}^u) \leq k + l$ implies that $u$ is reported at least $l + 1$ times - a contradiction.
— Analogously we obtain a contradiction if $u, w$ are satisfying (3.10$c$).

This shows that a set fulfilling the conditions (3.9) and (3.10) is indeed a $(kA + l(B \vee C))$-fault-tolerant dominating set.
Now let us show the necessity of conditions (3.9) and (3.10). If $D$ is not satisfying (3.9) then some vertex $u$ has not more than $k' + l'$ detectors in its closed neighbourhood, where $k', l'$ are such non-negative integers that $k' \leq k$ and $l' \leq l$. Then, if $l'$ detectors from $N[u]$ report $u$ and all the rest report $\emptyset$ we cannot state if there is an undesired event at $u$ or not.
Assume now that (3.9) is satisfied and (3.10) is not. It means that there exist $u, v \in V$ such that:

$$s_{uv} + s_{vu} + |Y| \leq 2k + 2l, \tag{3.11}$$

$$k + l + 1 \leq s_{uv} + |Y| \leq k + 2l, \tag{3.12}$$

$$k + l + 1 \leq s_{vu} + |Y| \leq k + 2l, \tag{3.13}$$

where $Y$ and $s_{uv}$ are defined in (3.3) and (3.4). For clarity we analyse two subcases.

*Subcase 1.* $t \geq 2l$.

Consider the following reporting:

— $l$ detectors from $Y$ report $u$,
— another $l$ detectors from $Y$ reports $v$,
— the rest of the detectors reports $\emptyset$.

Due to (3.12) and (3.13) we notice that not more than $k$ detectors from $N[u] \cap D$ and no more than $k$ detectors from $N[v] \cap D$ report $\emptyset$. Thus an undesired event might be at $u$ or might be at $v$ – in both possibilities there are not more than $k$ faults of type $A$ and $l$ faults of type $B$ or $C$.

*Subcase 2.* $t < 2l$. Observe that due to (3.11)-(3.13) there exist non-negative integers $t_u$, $t_v$ such that $t_u + t_v = t$, where

$$t_u + \max\{0, s_{uv} - k\} \leq l \text{ and } t_v + \max\{0, s_{vu} - k\} \leq l.$$

Consider the following reporting (Figure 3):

— $t_u$ detectors of $Y$ and $\max\{0, s_{uv} - k\}$ of $X_{uv}$ report $u$,
— another $t_v$ detectors of $Y$ and $\max\{0, s_{vu} - k\}$ of $X_{vu}$ report $v$,
— $\min\{k, s_{uv}\}$ of $X_{uv}$, $\min\{k, s_{vu}\}$ of $X_{vu}$ and all the rest report $\emptyset$.

In that case we also cannot be sure if there is an undesired event at $u$ or it is at $v$ – in both possibilities there are not more than $k$ faults of type $A$ and not more than $l$ faults of type $B$ or $C$, which ends the proof. □

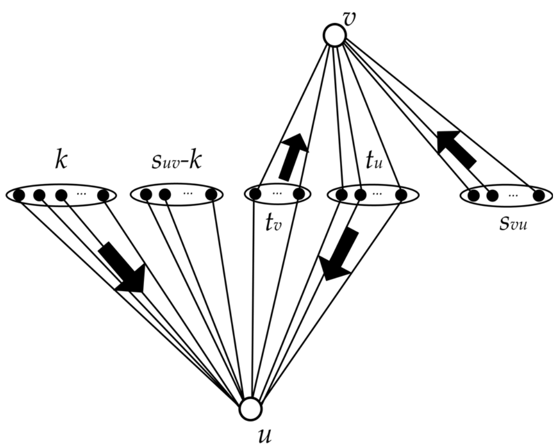


**Fig. 3.** The case when $s_{uv} > k$ and $s_{vu} \leq k$. Both $u$ and $v$ are possible locations of an undesired event

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