Eternal Domination of Generalized Petersen Graph

Ramy Shaheen and Ali Kassem

Department of Mathematics, Faculty of Science, Tishreen University, Latakia, Syria

Correspondence should be addressed to Ramy Shaheen; shaheenramy2010@hotmail.com

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An eternal dominating set of a graph $G$ is a set of guards distributed on the vertices of a dominating set so that each vertex can be occupied by one guard only. These guards can defend any infinite series of attacks; an attack is defended by moving one guard along an edge from its position to the attacked vertex. We consider the “all guards move” of the eternal dominating set problem, in which one guard has to move to the attacked vertex and all the remaining guards are allowed to move to an adjacent vertex or stay in their current positions after each attack in order to form a dominating set on the graph and at each step can be moved after each attack. The “all guards move model” is called the $m$-eternal domination model. The size of the smallest $m$-eternal dominating set is called the $m$-eternal domination number and is denoted by $\gamma_m^\infty(G)$. In this paper, we find $\gamma_m^\infty(P(n, 1))$ and $\gamma_m^\infty(P(n, 3))$ for $n \equiv 0 \pmod{4}$. We also find upper bounds for $\gamma_m^\infty(P(n, 2))$ and $\gamma_m^\infty(P(n, 3))$ when $n$ is arbitrary.

1. Introduction

The term graph protection refers to the process of placing guards or mobile agents in order to defend against a sequence of attacks on a network. Go to [1–5] for more background of the graph protection problem. Burger et al. introduced the concept of eternal domination in 2004 [2]. Goddard et al. introduced the “all guards move model” in [3]. General bounds of $\gamma(G) \leq \gamma_m^\infty(G) \leq \alpha(G)$ were determined in [3], where $\alpha(G)$ denotes the independence number of $G$ and $\gamma(G)$ denotes the domination number of $G$. The $m$-eternal domination numbers for cycles $C_n$ and paths $P_n$ were found by Goddard et al. [3] as follows: $\gamma_m^\infty(C_n) = \lfloor n/3 \rfloor$ and $\gamma_m^\infty(P_n) = \lceil n/2 \rceil$. For further information on eternal domination, see survey [1].

A generalized Petersen graph $P(n, k)$ is a graph with vertex set $V = \{v_1, v_2, \ldots, v_n\} \cup \{u_1, u_2, \ldots, u_n\}$ and edge set $E = \{v_i v_{i+1}, v_i u_{i+k}, u_i u_{i+k}\}$ with $v_{n+1} = v_1$, $u_{n+1} = u_1$, and $1 \leq i \leq n$ and $1 \leq k \leq \lfloor n/2 \rfloor$; see [6] for more information on generalized Petersen graph. The $k$-dominating graph $H(G, k)$ was defined by Goldwasser et al. in [7] as follows.

Let $G$ be a graph with a dominating set of cardinality $k$. The vertex set of the $k$-dominating graph $H(G, k)$, denoted $V(H)$, is the set of all subsets of $V(G)$ of size $k$ which are dominating sets and two vertices of $H$ are adjacent if and only if the $k$ guards occupying the vertices of $G$ of one can move (at most distance one each) to the vertices of the other, $\gamma_m^\infty(G) \leq k$. If and only if $H(G, k)$ has an induced subgraph $S(G, k)$ such that for each vertex $x$ of $S(G, k)$ the union of the vertices in the closed neighborhood of $x$ in $S(G, k)$ is equal to $V(G)$. A generalized Jahangir graph $I_{sm}$ for $m \geq 2$ is a graph on $sm + 1$ vertices, i.e., a graph consisting of a cycle $C_{sm}$ with one additional vertex which is adjacent to $m$ vertices of $C_{sm}$ at distance $s$ from each other on $C_{sm}$, see [8] for more information on the Jahangir graph. In [9], we found $\gamma_m^\infty(I_{sm})$ for $s \equiv 2, 3$. In [10], we found $\gamma_m^\infty(I_{sm})$ for $s, m$ are arbitrarily.

Proposition 1 [11]. For $n \geq 3$, we have $\gamma(P(n, 1)) = \begin{cases} \lfloor n/2 \rfloor & \text{for } n \equiv 0, 1 \pmod{4}, \\ (n/2) + 1 & \text{for } n \equiv 2 \pmod{4}. \end{cases}$
Proposition 2 [11]. For $n \geq 5$, we have $\gamma(P(n, 2)) = [3n/5]$.

Proposition 3 [11]. For $n \geq 7$, we have $\gamma(P(n, 3)) = \begin{cases} \lfloor n/2 \rfloor + 1 & \text{for } n \equiv 2 \pmod{4}, \\ \lfloor n/2 \rfloor & \text{for } n \equiv 0, 1 \pmod{4} \text{ or } n = 11, \\ \lfloor n/2 \rfloor + 1 & \text{for } n \equiv 3 \pmod{4}, n \neq 11. \end{cases}$

Proposition 4 [12]. For $n \geq 5$, we have $\alpha(P(n, 2)) = [4n/5]$.

Proposition 5 [12]. For $n \geq 7$, we have $\alpha(P(n, 3)) = \begin{cases} n \text{ if } n \text{ is even}, \\ n - 2 \text{ if } n \text{ is odd}. \end{cases}$

Proposition 6 [3]. For any graph $G$, $\gamma(G) \leq \gamma_{ec}^m(G) \leq \alpha(G)$.

2. Main Results

2.1. Eternal Domination Number of $P(n, 1)$. In this section, we find the $m$-eternal domination number of $P(n, 1)$ for $n$ is arbitrary.

Theorem 1. $\gamma_{ec}^m(P(n, 1)) = \begin{cases} \lfloor n/2 \rfloor & \text{for } n \equiv 0, 1, 3 \pmod{4}, \\ \lfloor n/2 \rfloor + 1 & \text{for } n \equiv 2 \pmod{4}. \end{cases}$

Proof. We consider all four cases of $n$.

Case 1 ($n \equiv 0 \pmod{4}$). Let $n = 4l : l \in \mathbb{N}$. As it was found in [11] that $\gamma(P(n, 1)) = n/2$ for this specific case and the $\gamma$-dominating set $S$ is the union of two sets $A$ and $B$ which are $A = \{v_{4i+1} : 0 \leq i \leq l - 1\}$, $B = \{u_{4i+3} : 0 \leq i \leq l - 1\}$.

We form the $k$-dominating graph $H(G, k)$ where $G = P(n, 1)$, $k = n/2$, and with sets $D_1 = A_1 \cup B_1 = \{v_{4i+1} : 0 \leq i \leq l - 1\} \cup \{u_{4i+3} : 0 \leq i \leq l - 1\}$, $D_2 = A_2 \cup B_2 = \{v_{4i+2} : 0 \leq i \leq l - 1\} \cup \{u_{4i+2} : 0 \leq i \leq l - 1\}$, $D_3 = A_3 \cup B_3 = \{v_{4i+3} : 0 \leq i \leq l - 1\} \cup \{u_{4i+4} : 0 \leq i \leq l - 1\}$, $D_4 = A_4 \cup B_4 = \{v_{4i+4} : 0 \leq i \leq l - 1\} \cup \{u_{4i+2} : 0 \leq i \leq l - 1\}$.

Each of these sets $D_1, D_2, D_3, D_4$ has a cardinality of $n/2$ and they are adjacent in $H(P(n, 1), n/2)$ for the following reasons. $D_1 \longrightarrow D_2 \longrightarrow D_3 \longrightarrow D_4 \longrightarrow D_1$ by rotating the guards one step clockwise. $D_2 \longrightarrow D_1 \longrightarrow D_3 \longrightarrow D_4 \longrightarrow D_2$ by rotating the guards one step counterclockwise. $D_1 \longrightarrow D_3 \longrightarrow D_1 \longrightarrow D_4 \longrightarrow D_2 \longrightarrow D_1$ by reflection which means moving the guards one step to occupy the corresponding unoccupied vertex on the other cycle.

Therefore, $D_1, D_2, D_3, D_4$ are adjacent in $S(P(n, 1), n/2)$ (the induced subgraph of $H(P(n, 1), n/2)$ on $D_1, D_2, D_3, D_4$ and $D_1 \cup D_2 \cup D_3 \cup D_4 = V(P(n, 1))$; therefore, we conclude that $\gamma_{ec}^m(P(n, 1)) \leq n/2$ for $n \equiv 0 \pmod{4}$ but $\gamma_{ec}^m(P(n, 1)) \geq \gamma(P(n, 1))$ from the definition of eternal domination; therefore, $\gamma_{ec}^m(P(n, 1)) = \gamma(P(n, 1)) = n/2$ for $n \equiv 0 \pmod{4}$; see Figure 1.

Case 2 ($n \equiv 1 \pmod{4}$). Let $n = 4l + 1 : l \in \mathbb{N}$. It was found in [11] that $\gamma(P(n, 1)) = [n/2]$ for this case and it was found that the $\gamma$-dominating set $S$ is $S = A \cup B \cup \{x, y\} : x, y \in \{v_{n-2}, v_n, u_{n-2}, u_n\}$.

We form the $k$-dominating graph $H(P(n, 1), [n/2])$ with the following sets of cardinality $[n/2]$: $D_1 = \{v_{4i+1} : 0 \leq i \leq l - 1\} \cup \{u_{4i+3} : 0 \leq i \leq l - 1\} \cup \{v_n\}$, $D_2 = \{v_{4i+2} : 0 \leq i \leq l - 1\} \cup \{u_{4i+2} : 0 \leq i \leq l - 1\} \cup \{u_n\}$, $D_3 = \{v_{4i+3} : 0 \leq i \leq l - 1\} \cup \{u_{4i+4} : 0 \leq i \leq l - 1\} \cup \{u_{n-1}\}$, $D_4 = \{v_{4i+4} : 0 \leq i \leq l - 1\} \cup \{u_{4i+2} : 0 \leq i \leq l - 1\} \cup \{v_n\}$.

It is easy to notice that $D_1, D_2, D_3, D_4$ are all adjacent in $H(P(n, 1), [n/2])$ and the union $D_1 \cup D_2 \cup D_3 \cup D_4 = V(P(n, 1))$; therefore, $\gamma_{ec}^m(P(n, 1)) \leq [n/2]$ for $n \equiv 1 \pmod{4}$ but we have $\gamma_{ec}^m(P(n, 1)) \geq \gamma(P(n, 1))$ from the definition of eternal domination; therefore, $\gamma_{ec}^m(P(n, 1)) = \gamma(P(n, 1)) = [n/2]$ for $n \equiv 1 \pmod{4}$; see Figure 2.

Case 3 ($n \equiv 2 \pmod{4}$). Let $n = 4l + 2 : l \in \mathbb{N}$. As it was found in [11], $\gamma(P(n, 1)) = (n/2) + 1$ for this specific case and the $\gamma$-dominating set $S$ is $S = A \cup B \cup \{x, y\} : x, y \in \{v_{n-1}, v_n, u_{n-1}, u_n\}$.

We form the $k$-dominating graph $H(P(n, 1), (n/2) + 1)$ with the following sets of the cardinality $(n/2) + 1$: $D_1 = \{v_{4i+1} : 0 \leq i \leq l - 1\} \cup \{u_{4i+3} : 0 \leq i \leq l - 1\} \cup \{v_{n-1}, u_n\}$, $D_2 = \{v_{4i+2} : 0 \leq i \leq l - 1\} \cup \{u_{4i+4} : 0 \leq i \leq l - 1\} \cup \{v_n\}$, $D_3 = \{v_{4i+3} : 0 \leq i \leq l - 1\} \cup \{u_{4i+1} : 0 \leq i \leq l - 1\} \cup \{v_n, u_{n-1}\}$, $D_4 = \{v_{4i+4} : 0 \leq i \leq l - 1\} \cup \{u_{4i+2} : 0 \leq i \leq l - 1\} \cup \{v_n, u_{n-1}\}$.

It is easy to notice that $D_1, D_2, D_3, D_4$ are all adjacent in $H(P(n, 1), (n/2) + 1)$ and the union of sets $D_1 \cup D_2 \cup D_3 \cup D_4 = V(P(n, 1))$; therefore, $\gamma_{ec}^m(P(n, 1)) \leq (n/2 + 1)$ for $n \equiv 1 \pmod{4}$, $\gamma_{ec}^m(P(n, 1)) \geq \gamma(P(n, 1))$; therefore, $\gamma_{ec}^m(P(n, 1)) = \gamma(P(n, 1)) = (n/2) + 1$; see Figure 3.

Case 4 ($n \equiv 3 \pmod{4}$). Let $n = 4l + 3 : l \in \mathbb{N}$. Ebrahimi et al. found in [11] that $\gamma(P(n, 1)) = [n/2]$ for this case and the $\gamma$-dominating set $S$ is $S = A \cup B \cup \{x, y\} : x, y \in \{v_{n-2}, v_{n-1}, v_n, u_{n-2}, u_{n-1}, u_n\}$. 
We form the $k$-dominating graph $H(P(n, 1), [n/2])$ with the following sets of cardinality $[n/2]$: 

\[ D_1 = \{v_{4i+1} : 0 \leq i \leq l-1\} \cup \{u_{4i+3} : 0 \leq i \leq l-1\} \cup \{v_{n-2}, u_n\}, \]

\[ D_2 = \{v_{4i+2} : 0 \leq i \leq l-1\} \cup \{u_{4i+4} : 0 \leq i \leq l-1\} \cup \{v_{n-1}, u_n\}, \]

\[ D_3 = \{v_{4i+3} : 0 \leq i \leq l-1\} \cup \{u_{4i+1} : 0 \leq i \leq l-1\} \cup \{u_{n-2}, v_n\}, \]

\[ D_4 = \{v_{4i+4} : 0 \leq i \leq l-1\} \cup \{u_{4i+2} : 0 \leq i \leq l-1\} \cup \{v_{n-1}, v_n\}. \] 

It is easy to notice that $D_1, D_2, D_3, D_4$ are all adjacent in $H(P(n, 1), [n/2])$ and the union $D_1 \cup D_2 \cup D_3 \cup D_4 = V(P(n, 1))$; therefore, $\gamma^c_m(P(n, 1)) \leq [n/2]$ for $n \equiv 3 \pmod{4}$ but $\gamma^c_m(P(n, 1)) \geq \gamma(P(n, 1))$; therefore, $\gamma^c_m(P(n, 1)) = \gamma(P(n, 1)) = \gamma(P(n, 1))$ for $n \equiv 3 \pmod{4}$; see Figure 4. From Cases 1–4, we conclude that $\gamma^c_m(P(n, 1)) = \gamma(P(n, 1))$ for $n \geq 3$.

2.2 Eternal Domination Number of $P(n, 2)$. In this section, we give an upper bound for the eternal domination number of generalized Petersen graph $P(n, 2)$.
Lemma 1. If we divide $P(n, 2)$ into $[n/5]$ blocks where each block consists of 10 vertices (5 vertices from the outer cycle and their 5 adjacent vertices from the inner cycle), then 4 guards are enough to eternally dominate each block.
Proof. We denote these blocks by \( B_j \): \( 1 \leq j \leq \lfloor n/5 \rfloor \); we also denote the subblock that remains in case \( n \not\equiv 0 \pmod{5} \) by \( SB \), keeping in mind that \( SB \) consists of 2, 4, 6, and 8 vertices when we have \( n \equiv 1, 2, 3, 4 \pmod{5} \), respectively. It was found in [11] that three vertices are enough to dominate each block \( B_j \) if the dominating vertices were distributed as shown in Figure 5.

To prove that four guards can eternally protect any block \( B_j \), it is enough to find a set of configurations for the guards so that these configurations cover all the vertices of \( B_j \) (every vertex of \( B_j \) belongs to at least one configuration) and every two configurations are reachable from each other in one step; we notice that the configurations presented in Figure 6 can achieve that; therefore, according to the definition of the \( k \)-dominating graph, we conclude that \( \gamma^\infty_m(B_j) \leq 4 \).

**Theorem 2.** For \( n \geq 5 \),

\[
\begin{align*}
\gamma^\infty_m(P(n, 2)) &= 4; n \in \{5, 6\}, \\
\gamma^\infty_m(P(7, 2)) &= 5, \\
\gamma^\infty_m(P(8, 2)) &= \{5, 6\}, \\
\gamma^\infty_m(P(n, 2)) &\leq \left\lceil \frac{3n}{5} \right\rceil + \left\lceil \frac{n}{10} \right\rceil ; n \geq 9 \text{ and } n \equiv 0 \pmod{10}, \\
\gamma^\infty_m(P(n, 2)) &\leq \left\lceil \frac{3n}{5} \right\rceil + \left\lfloor \frac{n}{10} \right\rfloor ; n \geq 9 \text{ and } n \equiv 0 \pmod{5} \text{ and } n \not\equiv 0 \pmod{10}, \\
\gamma^\infty_m(P(n, 2)) &\leq \left\lceil \frac{3n}{5} \right\rceil + \left\lfloor \frac{n}{10} \right\rfloor + l; n \equiv l \pmod{10} \text{ and } l = 1, 2, 3, \\
\gamma^\infty_m(P(n, 2)) &\leq \left\lceil \frac{3n}{5} \right\rceil + \left\lfloor \frac{n}{10} \right\rfloor + 2; n \equiv 4 \pmod{10}, \\
\gamma^\infty_m(P(n, 2)) &\leq \left\lceil \frac{3n}{5} \right\rceil + \left\lceil \frac{n}{10} \right\rceil + 3; n \equiv 4 \pmod{5} \text{ and } n \not\equiv 0 \pmod{10}.
\end{align*}
\]

Proof. We discuss all the cases as follows.

*Case i.1 (\( n = 5 \)).

From Propositions 2, 4, and 6, we conclude that

\( 3 \leq \gamma^\infty_m(P(5, 2)) \leq 4 \). 

(6)

By forming \( H(P(n, 2), 3) \) (the 3-dominating graph for \( P(n, 2) \)), we notice that \( V(H(P(n, 2), 3)) \) consists of the following sets:

\[
\begin{align*}
D_1 &= \{v_1, u_2, u_3, u_4\}, D_2 = \{v_2, u_1, u_4\}, D_3 = \{v_1, u_1, u_2, u_3\}, \\
D_4 &= \{v_4, u_1, u_2\}, D_5 = \{v_3, u_2, u_3\}, D_6 = \{v_1, v_2, v_3, u_4\}, \\
D_7 &= \{v_4, v_2, u_3\}, D_8 = \{v_3, v_1, u_4\}, D_9 = \{v_2, v_1, v_3, u_4\}, \\
D_{10} &= \{v_2, v_3, v_4, u_1\}.
\end{align*}
\]

(7)

Figure 7 illustrates \( H(P(n, 2), 3) \).

We denote the closed neighborhood of vertex \( D_i \) in \( H(P(n, 2), 3) \) by \( X_i \), and we notice the following:

\[
\begin{align*}
u_1 \notin X_1, u_2 \notin X_2, u_3 \notin X_3, u_4 \notin X_4, u_5 \notin X_5, v_2 \notin X_6, v_3 \\
\notin X_7, v_4 \notin X_8, v_5 \notin X_9, v_1 \notin X_{10}.
\end{align*}
\]

(8)

Therefore, by the definition of \( k \)-dominating graph, we conclude that \( \gamma^\infty_m(P(5, 2)) \not\equiv 3 \) which means \( \gamma^\infty_m(P(5, 2)) = 4 \) from (6).

We can easily prove that the following family is a 4-vertex eternal dominating family of \( (P(5, 2)) \):

\[
D_1 = \{v_1, v_2, u_4, u_3\}, D_2 = \{v_4, v_2, u_1, u_2\}, D_3 = \{v_1, v_3, u_3, u_4\}.
\]

(9)

*Case i.2 (\( n = 6 \)).

From Propositions 2, 4, and 6, we conclude that \( 4 \leq \gamma^\infty_m(P(6, 2)) \leq 4 \) which means \( \gamma^\infty_m(P(6, 2)) = 4 \) and the following family is a 4-vertex eternal dominating family of \( P(6, 2) \):

\[
D_1 = \{v_1, v_4, u_3, u_5\}, D_2 = \{v_2, v_5, u_1, u_4\}, D_3 = \{v_3, v_6, u_2, u_5\}.
\]

(10)

*Case ii (\( n = 7 \)).

From Propositions 2, 4, and 6, we conclude that \( \gamma^\infty_m(P(7, 2)) = 5 \). The following family is a 5-vertex eternal dominating family of \( P(7, 2) \):
ing into consideration the need to assign 4 guards to P
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fi
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7 guards assigned to these two blocks are enough to eternally protect these two blocks. Let us now con-
Therefore, the number of guards we assigned to B_1, B_2 is enough to eternally protect these two blocks. Let us now consider the next attack to occur on a vertex that does not belong to any of these two blocks; for example, the vertex denoted by v_{18} which is the middle “outer” vertex of B_1 and then the guards of B_1, B_2 return to configuration 1 of Figure 7 and at the same time the guards of B_3, B_4, B_5, B_6 move to configuration 3 of Figure 7. It is obvious that these configurations can be applied to all sets of blocks in P(n,2) which means without loss of generality the theory holds and we conclude that \( \gamma \text{me}(P(n,2)) \leq 3(n/5) + [n/10] \) in this case.

Case iii \((n = 8)\).
From Propositions 2, 4, and 6, it can be implied that
\[ 5 \leq \gamma \text{me}(P(8,2)) \leq 6. \]  
(12)

Case iv \((n \equiv 0 \pmod{10})\).
In this case, we have an even number of blocks that were defined in Lemma 1. For every pair of adjacent blocks, let us assign 3 guards to one of them and 4 guards to the other; we start by studying the first two blocks B_1, B_2; to prove that the 7 guards assigned to these two blocks are enough to eternally protect them, it is enough to find a set of guard configurations for which every vertex of \( V(B_1) \cup V(B_2) \) belongs to at least one of the configurations and every two configurations are reachable from one another in one step. We imply that the configurations shown in Figure 8 satisfy this purpose.

Therefore, the number of guards we assigned to B_1, B_2 is enough to eternally protect these two blocks. Let us now consider the next attack to occur on a vertex that does not belong to any of these two blocks; for example, the vertex denoted by v_{18} which is the middle “outer” vertex of B_1 and then the guards of B_1, B_2 return to configuration 1 of Figure 7 and at the same time the guards of B_3, B_4, B_5, B_6 move to configuration 3 of Figure 7. It is obvious that these configurations can be applied to all sets of blocks in P(n,2) which means without loss of generality the theory holds and we conclude that \( \gamma \text{me}(P(n,2)) \leq 3(n/5) + [n/10] \) in this case.

Case v \((n \equiv 9 \pmod{10})\).
In this case, we have an odd number of blocks that were defined in Lemma 1. This proof is equivalent to proving that the same distribution in Figure 7 of Case iv can eternally protect P(n,2) against an endless series of attacks taking into consideration the need to assign 4 guards to B_{n/5} in order to eternally protect it without the need to summon a guard from another block and that is because B_{n/5} does not belong to a pair (we have an odd number of blocks), which explains the need to have one additional guard in this case over Case iv.

Case vi \((n \equiv l \pmod{10})\) and \(l = 1, 2, 3\).
In this case, we have an even number of blocks that were defined in Lemma 1. This proof is equivalent to proving that the same distribution in Figure 7 of Case iv can eternally protect P(n,2) against an endless series of attacks taking into consideration the need to assign 4 guards to B_{n/5} in order to eternally protect it without the need to summon a guard from another block and that is because B_{n/5} does not belong to a pair (we have an odd number of blocks), which explains the need to have one additional guard in this case over Case iv.

As for the remaining pairs of blocks, we can simply apply the same configurations shown in Figure 8 of Case iv. Therefore, the theory holds for all the blocks and we prove the need for \( 3[n/5] + [n/10] + l - 1 \) guards when \( l = 1, 2, 3 \).

Case vii \((n \equiv l \pmod{5})\) and \(n \not\equiv l \pmod{10}\) and \(l = 1, 2, 3\).

This case is similar to Case vi with the exception that we need one additional guard on B_{n/5} because we have an odd number of blocks (similar to Case v).

Case viii \((n \equiv 4 \pmod{10})\).
This case is similar to Case vi, with the exception that we can eternally protect the 8-vertex subblock SB with 1-2 = 2 guards instead of 1-1 guards like in Case vi. Figure 12 shows the distributions of guards in this case.

Case ix \((n \equiv 4 \pmod{5})\) and \(n \not\equiv 4 \pmod{10}\).
This case is similar to Case viii with the exception that we need one additional guard on B_{n/5} because we have an odd number of blocks (similar to Cases v and vii).

We conclude that the theorem holds for all cases of \(n\).

2.3. Eternal Domination Number of \(P(n, 3)\). In this section, we find the eternal domination number of generalized Petersen graph \(P(n,3)\) when \(n \equiv 0 \pmod{4}\) and we give an upper bound for \(\gamma \text{me}(P(n,3))\) in the remaining cases: \(n \equiv 1, 2, 3 \pmod{4}\).

Theorem 3. \(\gamma \text{me}(P(n,3)) = n/2\) for \(n \equiv 0 \pmod{4}\).
Proof. Let \(n = 4l : l \in N\). From Proposition 3, we know that \(\gamma(P(n,3)) = n/2\) for this case and the \(\gamma\)-dominating set \(S\) is the union of two sets \(A\) and \(B\) which are \(A = \{v_{4i+1} : 0 \leq i \leq l - 1\}, B = \{u_{4i+3} : 0 \leq i \leq l - 1\}\). Therefore, according to Propositions 3 and 5, the trivial bounds for \(\gamma \text{me}(P(n,3))\) are \(n/2 \leq \gamma \text{me}(P(n,3)) \leq n\).

We form the \(k\)-dominating graph \(H(G,k)\) where \(G = P(n,3), k = n/2\), and with sets
\begin{align*}
D_1 &= A_1 \cup B_1 = \{v_{4i+1} : 0 \leq i \leq l - 1\} \cup \{u_{4i+3} : 0 \leq i \leq l - 1\}, \\
D_2 &= A_2 \cup B_2 = \{v_{4i+2} : 0 \leq i \leq l - 1\} \cup \{u_{4i+4} : 0 \leq i \leq l - 1\}, \\
D_3 &= A_3 \cup B_3 = \{v_{4i+3} : 0 \leq i \leq l - 1\} \cup \{u_{4i+1} : 0 \leq i \leq l - 1\}, \\
D_4 &= A_4 \cup B_4 = \{v_{4i+4} : 0 \leq i \leq l - 1\} \cup \{u_{4i+2} : 0 \leq i \leq l - 1\}.
\end{align*}
(13)

Each of these sets \(D_1, D_2, D_3, D_4\) has a cardinality of \(n/2\) and they are all adjacent in \(H(P(n,3), n/2)\) for the following reasons.
\(D_1 \rightarrow D_2, D_2 \rightarrow D_3, D_3 \rightarrow D_4, D_4 \rightarrow D_1\) by rotating the guards of the outer cycle one step clockwise and rotating the guards of the inner cycle one step counterclockwise.
\(D_1 \rightarrow D_4, D_2 \rightarrow D_1, D_3 \rightarrow D_2, D_4 \rightarrow D_3\) by rotating the guards on the outer cycle one step
Figure 8: Eternally protecting $B_1, B_2$ with 7 guards.

Figure 9: Eternally protecting $B_1, B_2, SB$ with 8 guards.

Figure 10: Eternally protecting $B_1, B_2, SB$ with 9 guards.
Figure 11: Eternally protecting $B_1, B_2, SB$ with 10 guards.

Figure 12: Eternally protecting $B_1, B_2, SB$ with 10 guards.

Figure 13: $\gamma_m^0(P(12, 3)) = \gamma(P(12, 3)) = 6$.

Figure 14: Eternally protecting $P(13, 3)$ with 8 guards.
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with these sets of cardinality two sets and
D
clockwise and rotating the guards of the inner
cycle one step clockwise.

Therefore, D₁, D₂, D₃, D₄ are adjacent in S(P(n, 3), n/2) (the induced subgraph of H(P(n, 3), n/2) on D₁, D₂, D₃, D₄ and D₁ ∪ D₂ ∪ D₃ ∪ D₄ = V(P(n, 3)); therefore, we conclude that γ_m^{co}(P(n, 3)) ≤ n/2 for n = 0 (mod 4) but γ_m^{co}(P(n, 1)) ≥ γ(P(n, 1)) from the definition of eternal domination, so γ_m^{co}(P(n, 3)) = γ(P(n, 3)) = n/2 for n = 0 (mod 4); see Figure 13.

This proof proposes the following idea.

For n = 1, 2, 3 (mod 4), we can divide V(P(n, 3)) into
two sets X and Y defined as

\[ X = \{v_i, u_i; 1 ≤ i ≤ 4l\} ; n = 1, 2, 3 \mod 4, \]

\[ Y = \begin{cases} 
\{v_{i+1}, u_{i+1}; n = 1 \mod 4, \}
\{v_{i+1}, v_{i+2}, u_{i+1}, u_{i+2}; n = 2 \mod 4, \}
\{v_{i+1}, v_{i+2}, v_{i+3}, u_{i+1}, u_{i+2}, u_{i+3}; n = 3 \mod 4. \}
\end{cases} \]

We notice that any change of n equals a change in
the number of the vertices of X; meanwhile, the number of the vertices of Y does not change. We can use this observation to study the eternal domination problem on P(n, 3) when n = 1, 2, 3 (mod 4), because this observation allows us to take the relationships between the guards situated on the vertices of Y and the end vertices of X of one example “one value of n” then generalize these relationships for any value of n, taking into consideration that the relationships between the guards situated on the inner vertices of X will always be similar to the ones in Theorem 3.

**Theorem 4.** For n ≥ 7, we have γ_m^{co}(P(n, 3)) ≤ \[ \begin{cases} 
\lceil n/2 \rceil + 1 ; n = 1 \mod 4, \\
(n/2) + 2 ; n = 2 \mod 4, \\
\lceil n/2 \rceil + 2 ; n = 3 \mod 4. 
\end{cases} \]

**Case 1** (n ≥ 9 and n = 1 (mod 4)). Let n = 4l + 1 : l ∈ N. From Proposition 3, we know that γ(P(n, 3)) = \lceil n/2 \rceil for this case and the γ-dominating set S is S = A ∪ B \{v_{n-1}, u_{n-1} \}. Therefore, according to Propositions 3 and 5, the trivial bounds for γ_m^{co}(P(n, 3)) are \lceil n/2 \rceil ≤ γ_m^{co}(P(n, 3)) ≤ n.

We form the k-dominating graph H(P(n, 3), \lceil n/2 \rceil + 1) with these sets of cardinality \lceil n/2 \rceil + 1:

\[ D_1 = \{v_{4i+1}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+1}; 0 ≤ i ≤ l - 1\} ∪ \{v_n, u_{n-1} \}, \]

\[ D_2 = \{v_{4i+2}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+2}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, u_n \}, \]

\[ D_3 = \{v_{4i+3}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+3}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, u_n \}, \]

\[ D_4 = \{v_{4i+4}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+4}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, u_n \}. \]

**Case 2** (n ≥ 10 and n = 2 (mod 4)). Let n = 4l + 2 : l ∈ N. From Proposition 3, we know that γ(P(n, 3)) = \(n/2\) + 1 for this case and the γ-dominating set S is S = A ∪ B \{v_{n-1}, u_{n-1} \}. Then, according to Propositions 3 and 5, the trivial bounds for γ_m^{co}(P(n, 3)) in this case are \(n/2\) + 1 ≤ γ_m^{co}(P(n, 3)) ≤ n.

We form the k-dominating graph H(P(n, 3), \(n/2\) + 2) with these sets of cardinality \(n/2\) + 2:

\[ D_1 = \{v_{4i+1}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+1}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, v_{n-1}, u_{n-1} \}, \]

\[ D_2 = \{v_{4i+2}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+2}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, u_{n}, u_{n} \}, \]

\[ D_3 = \{v_{4i+3}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+3}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, v_{n-1}, u_{n-1} \}, \]

\[ D_4 = \{v_{4i+4}; 0 ≤ i ≤ l - 1\} ∪ \{u_{4i+4}; 0 ≤ i ≤ l - 1\} ∪ \{v_{n-1}, u_{n-1} \}. \]

See Figure 15.
We form the $k$-dominating graph $H(P(n, 3), \lceil n/2 \rceil + 2)$ with these sets of cardinality $\lceil n/2 \rceil + 2$:

$$\begin{align*}
D_1 &= \{v_{k+1} : 0 \leq i \leq l - 1\} \cup \{u_{k+1} : 0 \leq i \leq l - 1\} \cup \{v_{k+2} : 0 \leq i \leq l - 1\} \cup \{u_{k+2} : 0 \leq i \leq l - 1\} \\
D_2 &= \{v_{k+1} : 0 \leq i \leq l - 1\} \cup \{u_{k+1} : 0 \leq i \leq l - 1\} \cup \{v_{k+3} : 0 \leq i \leq l - 1\} \cup \{u_{k+3} : 0 \leq i \leq l - 1\} \\
D_3 &= \{v_{k+1} : 0 \leq i \leq l - 1\} \cup \{u_{k+1} : 0 \leq i \leq l - 1\} \cup \{v_{k+4} : 0 \leq i \leq l - 1\} \cup \{u_{k+4} : 0 \leq i \leq l - 1\} \\
D_4 &= \{v_{k+1} : 0 \leq i \leq l - 1\} \cup \{u_{k+1} : 0 \leq i \leq l - 1\} \\
\end{align*}$$  

(17)

It is easy to notice that $D_1, D_2, D_3, D_4$ are all adjacent in $H(P(n, 3), \lceil n/2 \rceil + 2)$ and the union $D_1 \cup D_2 \cup D_3 \cup D_4 = V(P(n, 3))$; therefore, $\chi_m^*(P(n, 3)) \leq \lceil n/2 \rceil + 2$ for $n \equiv 3 \pmod{4}$. See Figure 16.

From Cases 1–3, we conclude the requested.

**Data Availability**

No data were used to support this study.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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