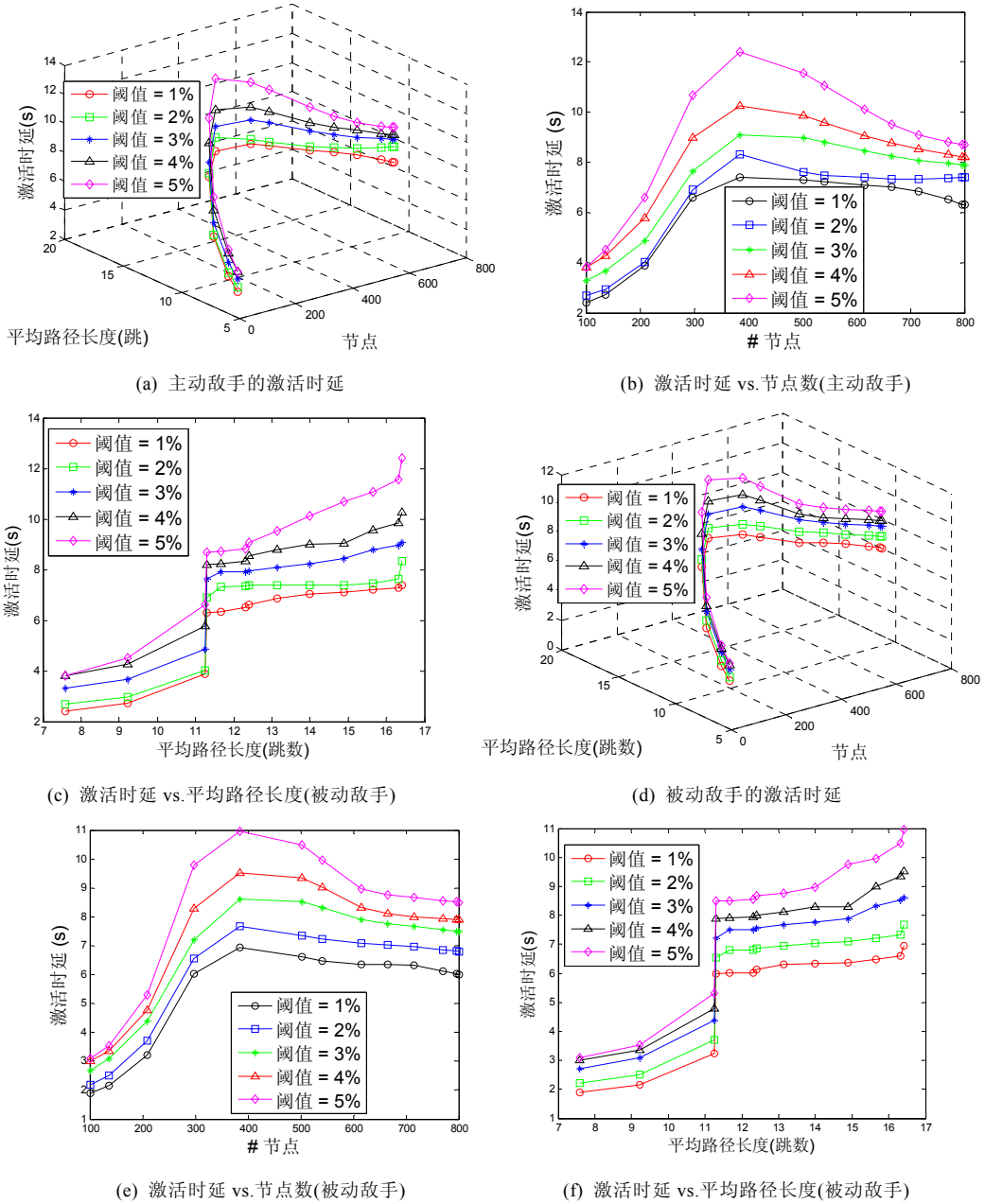
的原因是:节点数量增多时,网络总流量提高并且网络的路径变化增大,这些变化容易被 Sink 节点发现.另外,阈值和网络规模相同时,对于主动敌手的探测漏报率比探测被动敌手的漏报率更低.这是因为主动敌手采取了反探测策略,如随机转发或篡改数据包,反而让 Sink 能更容易判断攻击发生.

图 10 展示了 Pworm 在不同阈值和敌手模型下的激活时延.



(a) 主动敌手的激活时延

(b) 激活时延 vs.节点数(主动敌手)

(c) 激活时延 vs.平均路径长度(被动敌手)

(d) 被动敌手的激活时延

(e) 激活时延 vs.节点数(被动敌手)

(f) 激活时延 vs.平均路径长度(被动敌手)

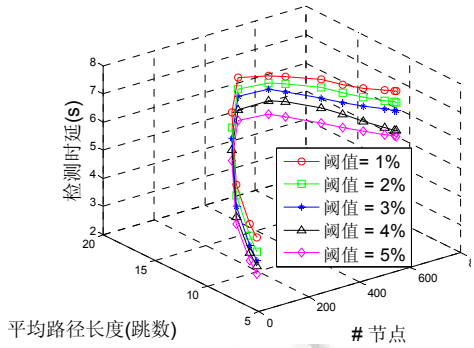
Fig.10 Activation latency shown for active and Passive adversaries

图 10 主动敌手和被动敌手的激活延迟变化

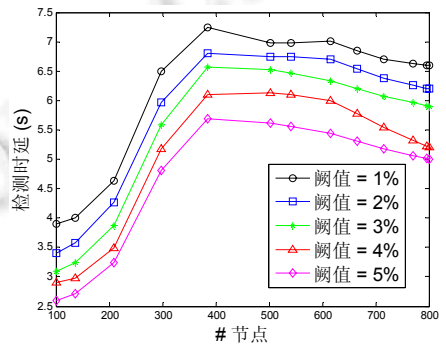
从图 10 中可以看出,激活时延变化趋势为:激活时延先随着网络规模的增大而增长;当网络规模达到 300 个~400 个节点时,激活时延的值最大;之后,激活时延的值逐渐缩短.原因主要来自两方面:首先,当网络规模较少

时,网络路径较短,此时,Sink 节点能很快地收集网络拓扑信息,这时,激活时延也较短;其次,当节点数量大于 300 个节点时,随着节点数量增大,网络中节点更加密集,每个节点几乎都能找到一条更短的路径到达 Sink 节点,使得网络平均路径长度反而变短,此时,激活时延减少.图 10(c)为激活时延随网络平均路径长度的变化关系,可以看出:网络规模小时,激活时延较短.图 10(d)~图 10(f)所示被动敌手模型中,激活时延的变化情况类似于图 10(b),但阈值相同时,被动敌手中激活时延的值比主动敌手中更少.

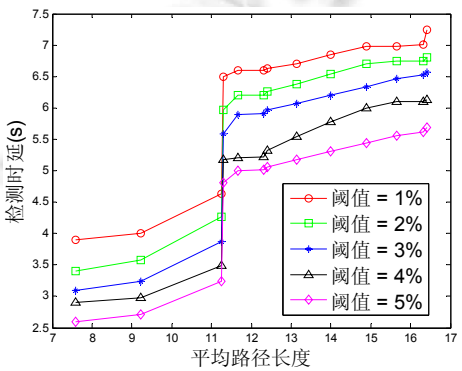
图 11 为不同阈值和敌手模型下的检测时延.检测时延的变化非常类似于激活时延的变化情况,只是检测时延的值略高.



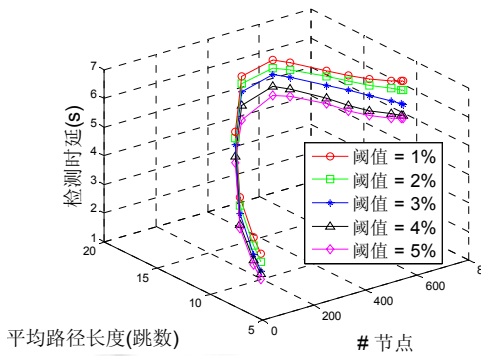
(a) 主动敌手的检测时延



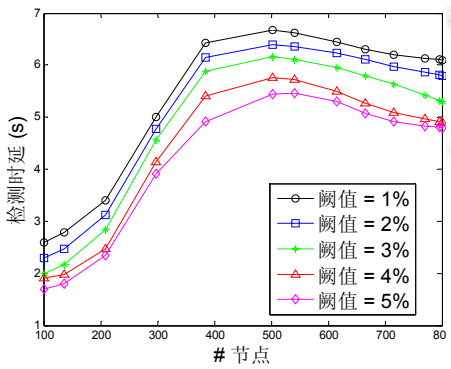
(b) 检测时延 vs.节点数(主动敌手)



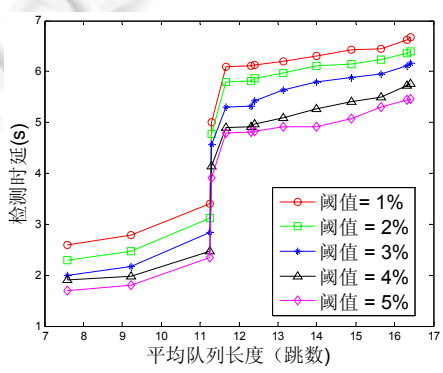
(c) 检测时延 vs.平均路径长度(被动敌手)



(d) 被动敌手的检测时延



(e) 被动敌手的检测时延



(f) 检测时延 vs.平均路径长度(被动敌手)

Fig.11 Detection latency shown for active and passive adversaries

图 11 主动敌手和被动敌手的激活检测变化

我们可以看出:网络中节点数量越多时,网络的总流量和路径的长度越大.此时,Sink 节点收集网络路径所需时间也变长,使得检测时延增大.

总之,由图 10 和图 11 可见:阈值较大时,激活时延和检测时延均增长.这是因为阈值较大时,Sink 节点需要较长时间来观测变化路径的比例.不同阈值时,检测时延和激活时延的变化规律一致,均为网络规模较小时,时延以较快的速度提升到一个最大值;之后,随着网络越来越密集而降低.图 10(c)、图 10(f)以及图 11(c)、图 11(f)中,网络平均路径长度的变化也遵循先增大后减小的趋势.路径长度短时,两种时延的值均较小;反之,网络规模的增大,引起延迟和平均路径长度均增大.

6 结 论

对于无线传感器网络和无线自组织网络而言,虫洞攻击是最严重的威胁之一.现有的虫洞探测方法或者需要较强的网络拓扑假设,或需要额外硬件等,这些问题限制了现有方法在传感器网络中的应用.本文基于虫洞节点对网络流量和拓扑影响的观察,提出了一个轻量级、被动式、实时的虫洞攻击探测方案 Pworm.通过安全包标记,我们将检测过程融入正常的数据包转发过程中,再利用虫洞攻击的两个特征——路径变化和路径长度缩短对虫洞进行实时检测.因此,Pworm 不仅能探测主动和被动虫洞敌手,还能定位虫洞的位置.实验结果表明:我们的方案误报率为 0,漏报率低于 5%,整体时延不超过 14s,能实时、准确的检测虫洞节点.

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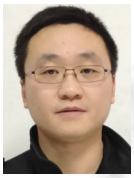

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